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ORBITING SPACE DEBRIS: DANGERS, MEASUREMENT AND MITIGATION

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1 June 1992

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13. ABSTRACT (Maximum 200 words)

Space debris is a growing environmental problem. Accumulation of objects in Earth orbit threatens space systems through the possibility of collisions and runaway debris multiplication.The amount of debris in orbit is uncertain due to the lack of information on the population of debris between 1 and 10 centimeters diameter. Collisions with debris even smaller than 1 cm can be catastrophic due to the high orbital velocities involved. Research efforts are under way at NASA, United States Space Command and the Air force Phillips Laboratory to detect and catalog the debris population in near-Earth space. Current international and national laws are inadequate to control the proliferation of space debris.

Space debris is a serious problem with large economic, military, technical and diplomatic components. Actions need to be taken now to: determine the full extent of the orbital debris problem; accurately predict the future evolution of the debris population; decide the extent of the debris mitigation procedures required; implement these policies on a global basis via an international treaty. Action must be initiated now, before the loss of critical space systems such as the Space Shuttle or the Space Station.

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1. INTRODUCTION

With the continued use of space for commercial, military, and scientific purposes, the number of objects orbiting the Earth has steadily increased over the past 33 years. There are now over 7000 objects larger than 10 centimeters[1] and an estimated 30,000 to 70,000 smaller objects, 1-10 cm long in Earth orbit. There are an estimated 10 billion objects in the range of 0.1 mm to 1 cm in Earth orbit.[2] The large number of objects in orbit raises the threat of debris colliding with important functional spacecraft. The increase in the amount of space debris is a growing problem that has the potential to limit the future use of near Earth orbits.

Space debris is defined as any object that is in orbit around the earth not in use, or controlled, or of any scientific or economic value (for example objects that have been discarded and left in orbit at the end of their useful lives). Space debris includes old, non-operational

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Received for Publication 20 April 1992

1 United States Space Command, Space Analysis and Data Branch (1991) *Space Surveillance Center Catalog*, United States Space Command, Cheyenne Mountain Air Force Base, Colorado.

2 European Space Agency (1988) *Space Debris: A Report from the European Space Agency Space Debris Working Group*, France: European Space Agency, ESA SP-1109, p.15.

satellites, used rocket boosters/bodies, and parts of satellites discarded during operations. It also includes fragments of objects that have disintegrated through intentional or accidental explosion or collision, and objects as small as paint chips that have broken off satellites. The number of objects in orbit that are 10 centimeter or larger is growing at an average rate of 240 per year.[3] The growth rate of smaller objects is unknown due to the uncertainty of the number and size of small debris produced by events such as satellite fragmentation.

The distribution around the Earth of the largest space objects, those large enough to be tracked by the United States Air Force Space Surveillance System, is shown in Figure 1 and Figure 2. Figure 1 shows the location of all objects tracked by the United States in near Earth orbits at an instant in time. Figure 2 shows a wider view of Earth orbit that includes the geosynchronous ring, with its high percentage of satellites clearly visible.

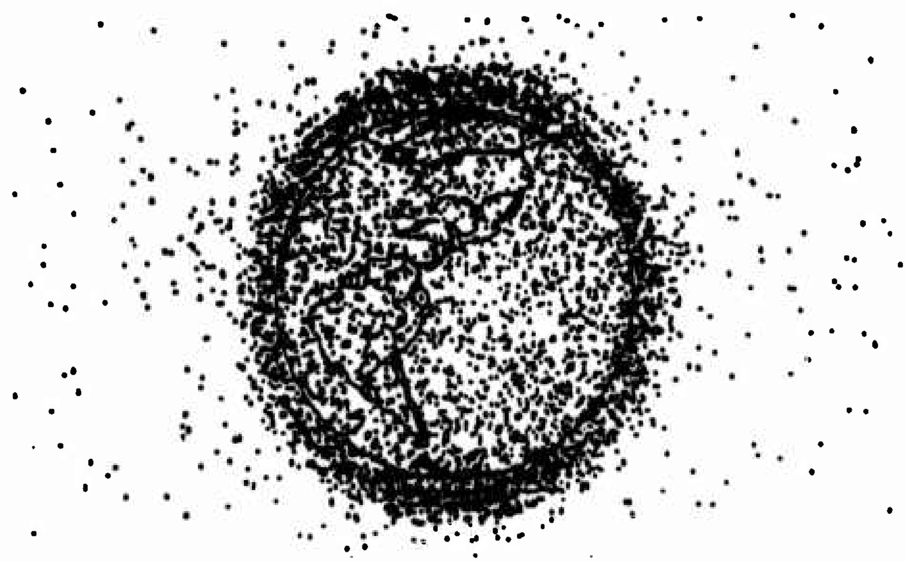


Figure 1. Locations of Near Earth Orbit Objects Contained in the Space Command Satellite Catalog at 0000 GMT, 1 January 1989

[3] Based on US Space Command Catalog.

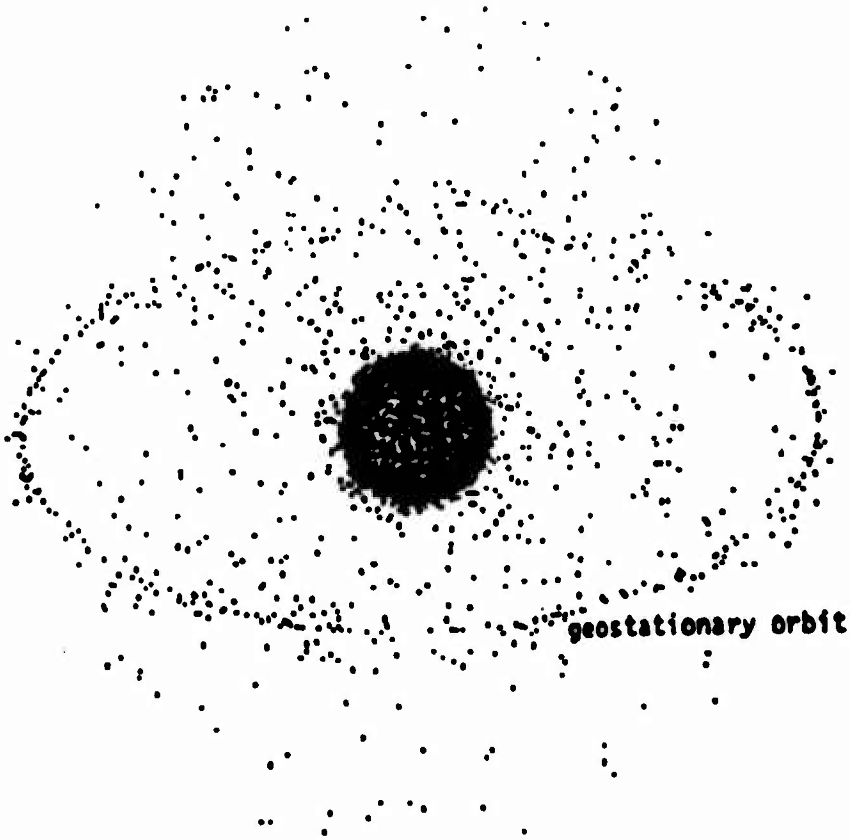


Figure 2. Positions of All Objects Contained in the Space Command Satellite Catalog at 0000 GMT, 1 January 1989

1.1 Background Environment

Space debris has been accumulating since man first started launching objects into orbit. In fact Explorer 1, the third satellite ever launched and the one that discovered the Van Allen radiation belts, is still in orbit and will remain there for the next several thousand years.

In 1988 there were an estimated 2,000,000 kg of manmade objects in Earth orbit.[2] These objects range in size from large satellites and space stations, to wrenches dropped by astronauts, to paint chips and small solid rocket exhaust particles. Many of these objects are in long lived orbits and will remain in orbit for the foreseeable future.

The 30,000 to 70,000 objects in orbit that are larger than 1 cm are typically metal, either aluminum, steel, or titanium, and they are found in approximately the same proportion as each is used in building spacecraft. These objects typically have a high ballistic coefficient which gives them longer lifetimes on orbit, while increasing the possibility of damaging other space systems.

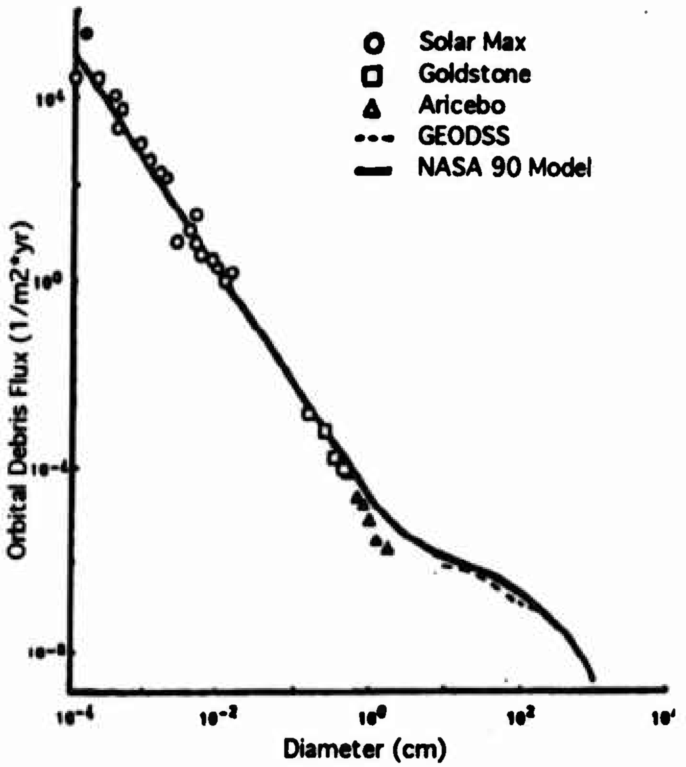
There is also a natural meteor background that poses similar threats as space debris to space systems. An accepted estimate of the mass of near-earth meteors within a volume of 2000 km radius around the Earth is 300 kg at any one time. These meteors are on a hyperbolic trajectory and move very quickly through the space near Earth. Meteors can be rocks, dust, ice, or a number of other substances. Typical velocities of meteors are on the order of 20 km/sec. At these velocities, most sub-millimeter sized meteors vaporize on contact and do not cause significant structural damage.

Manmade objects are typically in near-Earth orbit where they circle the Earth and remain a threat to other near-Earth space systems. While natural meteors and micrometeors only have one chance of colliding with a particular object as they pass by the Earth, an object in Earth orbit has two chances of collision on every orbit.

In order to characterize the threat to space systems it is important to know the characteristics of debris. This includes the number, size, altitude, orbit and composition of the debris. (These details are covered in detail in Section 3.) An effective method for illustrating the chances of collision with debris is with the cumulative collision flux. The cumulative collisional flux has units of collisions per square meter per year. It gives the expected flux of objects with a given size or larger through a one meter square area in near-Earth space for one year. The collisional flux along an orbit is a function of its altitude and inclination and the debris environment. NASA has developed a computer based model to aid in determining the cumulative collisional flux. Figure 3 shows the collisional probability for low Earth orbit as a function of size.

To find the collisional probability, multiply the orbital debris flux by the projected surface area for the spacecraft and the number of years in operation. Because of the rapidly increasing number of objects in orbit the probability of collision between satellites and space debris has increased dramatically over the past few decades.

One important aspect of the debris problem to consider is that the size of the debris that is considered dangerous to space operations is very small (1 mm) due to their very high orbital velocities. Collision velocities between two near-Earth orbiting objects can reach as high as 15 km/sec, but the mean is on the order of 10 km/sec or 22,500 miles per hour. Collisions at this velocity are known as hypervelocity collisions or impacts. Types of hypervelocity impact damage include penetration, perforation, detached spall, local deformation, erosion and fractures. Failure modes associated with these types of collision can range from catastrophic rupture of a pressurized module, to explosions of fuel tanks, or degradation of performance of a solar array.



Orbital Flux vs. Diameter, at 500 km altitude, and 28.5 deg inclination in 1988

Figure 3. Cumulative Collisional Flux per Square Meter per Year as a Function of Size for Low Earth Orbiting Satellites[4]

Because of the high kinetic energy associated with even very small hypervelocity objects, objects as small as paint chips are significant. Collisions with debris as small as 1 mm could be catastrophic for many space systems. During the Space Shuttle Mission STS-7, a 0.2-mm paint fleck impacted on the shuttle's side window. Although it did not puncture the window, it did require replacing the window prior to the next flight, a $50,000 repair. The Space Station's pressurized modules are going to be protected by shields and bumpers to withstand collisions with objects 1 cm or smaller in size, but at considerable cost and additional weight. Most other space systems are constructed to minimize weight and are not as well shielded for protection against space debris as the space station or space shuttle. All satellites are very vulnerable to the types of damage done by space debris. Satellites rely on an extensive set of electronic components

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[4] Orion International Technologies (1991) Program Review: Long Term Debris Propagation Models (Space Debris). Orion International Technologies.

which are double or triple redundant to ensure successful mission completion. If a small piece of debris penetrates an electronics box of a satellite, the system will fail and the only indication the operators may receive is loss of communication and control of the satellite. With most deployed space systems currently on orbit, an object smaller than one-half cm diameter is adequate to penetrate and destroy the satellite. Section 4 discusses damage scenarios and provides results from hypervelocity impact studies. Table 1 lists the most likely critical types of failure for various subsystems due to collisions with debris.

Table 1. Critical Types of Failure for Various Subsystems Due to Hypervelocity Impacts

	Subsystems					
Probable Critical Types of Failure	Pressure Cabins	Tanks	Radiators	Windows	Electronics	Special Surfaces
Catastrophic Rupture	x	x		x		
Detached Spalling	x	x	x		x	
Secondary Factures			x		x	
Leakage	x	x	x			
Shock Pulse	x			x	x	
Vapor Flash	x					
Deflagration		x				
Deformation			x		x	
Reduced Residual Strength	x	x	x	x		
Fluid Contamination		x	x			
Thermal Insulation Damage	x	x				
Obscuration				x		
Erosion				x		x

NASA SP-8042, Meteoroid Damage Assessment, Space Vehicle Design Criteria (Structures), May 1970, obtained from E.L. Christiansen briefing "Meteor/Debris Shielding", 2 April 1991.

1.2 Current Interest In Space Debris

Space debris is a relatively new environmental concern. The amount of objects we leave in orbit by intentional or unintentional acts has increased over the past thirty years. These uncontrolled and discarded objects in space are becoming a major threat to future space systems. In fact, space debris is now considered the largest threat to the proposed International Space Station Freedom. If the debris continues to be produced at its current rate, the probability of the

Space Station colliding with a piece of space debris 1 cm or larger over a 30 year mission is 9-14 percent.[5]

Other proposed large systems, such as the proposed Strategic Defense Initiative's Brilliant Pebbles system being designed to protect the United States from ballistic missile attack, and the Air Force's proposed Space Based Radar system designed to provide radar data during hostile bomber attack, will face similar threats of collision with the increasing number of space objects.

1.3 Policy Developments

Space debris has recently gained significant attention in some space organizations and in the media. The first significant report on space debris was from a military perspective and was provided in the Air Force Scientific Advisory Board's report in December 1987 titled "Current and Potential Technology to Protect Air Force Space Missions from Current and Future Debris".[6] In November 1988, the European Space Agency published a report titled "Space Debris".[2] In September 1990, the Office of Technology Assessment published the report "Orbiting Debris: A Space Environmental Problem".[7] These reports were the first official expressions of concern in the space community on the issue of space debris. Many organizations such as the American Institute of Aeronautics and Astronautics (AIAA) have been investigating the threat of space debris for space activities and methods to control it. Specialized classes are now available through AIAA to educate the aerospace community about the problems associated with space debris. Space debris even has its own dedicated periodical, titled "The Orbital Debris Monitor".[8]

While all this attention has increased the awareness of the problem, it has not provided clear solutions. Problems exist with determining the number, size, and distribution of existing orbital debris. Modelling efforts are based to a great extent on broad, generalized assumptions that make their confidence levels very low. To improve these models, more data is required on the amount of debris and their production rates and mechanisms.

Controversy exists over what effects the proposed increased launch activities associated with such programs as the Strategic Defense Initiative's Brilliant Pebbles or the commercial Iridium communications satellites will have on the debris population. Other concerns include the effects of anti-satellite weapons programs and tests.

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5 Rex D. (1990) European investigations on space debris, presented at the Orbital Debris Workshop IIII, ESA Space Debris Working Group, Technical University of Braunschweig, Federal Republic of Germany, also, Advances in Space Research, **10** (No.3-4):347-352.

6 United States Air Force Scientific Advisory Board (1987) *Report of the Ad Hoc Committee on Current and Potential Technology to Protect Air Force Space Missions from Current and Future Debris*, United States Air Force Scientific Advisory Board.

7 United States Congress, Office of Technology Assessment (1990) *Orbiting Debris: A Space Environmental Problem--Background Paper, OTA-BP-ISC-72*, Washington, D.C.: U.S. Government Printing Office.

8 "The Orbital Debris Monitor" is published by Darrin McKnight. Information is available at 12624 Verny Place, Fairfax, VA 22033-4383.

Another major concern is the possibility of the Kessler Effect. The Kessler Effect describes the possibility of self generation of debris due to random collision between objects in space. The problem is that space objects will eventually randomly collide with other space objects creating a large number of smaller but more numerous debris. This then increases the risk of further collisions and the creation of additional debris. This self generation of additional debris could outpace the removal mechanism due to atmospheric drag in higher orbits, thus creating an unstable, increasing population of space debris. This effect has the potential for rendering certain orbits unusable for any manned or mission-essential spacecraft.

The Kessler Effect was advanced by Donald Kessler of NASA. His research indicates that in certain altitude regimes the critical number of objects and mass has already been exceeded and the generation of additional debris caused by collisions between objects will outpace the removal rate by atmospheric drag. If this is true, then the problem will get worse even if there are no additional objects placed in orbit. This concept is gaining wider acceptance within the scientific community. The Kessler Effect will be discussed in greater detail in Section 2.

Given all the unknowns, uncertainties and controversies associated with space debris, remedial steps need to be taken in order to solve or at least minimize the problem. These steps will require money and effort. With all the recent publicity this issue has received, money and effort may become available. However, as with any environmental issue, the organizations funding the program want immediate results. While attention is focused on this issue, it is important to develop a comprehensive program that can survive the political and emotional arguments and proceed to develop accurate assessments of the risk of space debris and sound recommendations for its elimination in the future.

1.4 Areas to be Covered in This Report

This report discusses the many aspects of the space debris problem. After this introduction, Section 2 will focus on the history of space debris accumulation and the various types of debris and their sources and available information on each. Section 3 will address the space debris environment, including the distribution of debris in terms of size, altitude and inclination.

Section 4 discusses the hazards associated with space debris and assesses the risk to space systems, and Section 5 examines the current space surveillance systems used for tracking large space objects and their limitations in tracking small objects. Section 6 addresses existing and proposed measurement programs designed to provide a better understanding of the space debris environment. Section 7 discusses possible mitigation efforts to limit the growth and effects of space debris. Section 8 will discuss the legal implications of space debris, focusing on both international and domestic laws and regulations. Finally, Section 9 will provide some recommendations for future policies to limit the growth of the space debris population.

2. THE HISTORY OF SPACE DEBRIS ACCUMULATION

This section will discuss the types and sources of space debris. It begins with a description of several launches of current satellite systems. The gradual accumulation of debris in orbit will be discussed. An extensive discussion of fragmentation debris -- the largest source of orbital debris -- and its causes will follow. The last part of this section discusses the natural removal mechanisms for debris.

2.1 "Typical" Space Launches

During a typical space launch a number of objects are discarded and left in orbit. This number depends on the specific satellite and how strictly debris abatement policies are enforced. The core of the debris problem is that once a spacecraft has reached orbit, any and all discarded objects will remain in a similar orbit with similar lifetimes as the satellite.

2.1.1 DEFENSE METEOROLOGICAL SATELLITE PROGRAM SATELLITE

The Defense Meteorological Satellite Program (DMSP) satellite resides in a sun-synchronous 450 nautical mile orbit inclined at 98.75 degrees to the equator, one of the highest debris populated orbits. DMSP provides global cloud data and other specialized meteorological data to the Department of Defense in support of its world-wide operations.

The DMSP satellite is launched on an Atlas E launch vehicle. Only the satellite and the satellite kick booster are placed into orbit. All other booster debris, such as the flaring and clamp bands, quickly falls back to Earth prior to reaching orbit. When the satellite reaches the proper orbit the kick motor is released and becomes debris. These types of upper stage kick motors have become a substantial source of small debris due to explosions that have occurred years after deployment of the satellite. This issue will be discussed in depth later in this section.

During initialization of the DMSP satellite, several objects are released into the operational orbit; these objects include bands, cords and covers. Two bands per satellite are used to secure the solar array for launch. Each band is made of 3/32 inch stainless steel and is 165 inches long. These bands are cut and released as debris during deployment of the solar arrays. Two other cords secure a glare obstructor that shields the sensors from extraneous light. These two cords, which are 3/64 inch diameter kevlar and 18 inches long, are also released as debris. These kevlar cords are not detectable by the current space surveillance radar systems used by the United States.

During initialization of the DMSP spacecraft, two covers (the radiator cover and the optical cover), intended to protect instruments and other parts of the spacecraft during preparations and launch, are released as debris. The radiator cover is kapton coated urethane on a metal frame and is 11 x 11 x 1 inches and weighs approximately 1/2 pound. The other cover is the optics cover. This nickel and copper coated epoxy glass panel is approximately 9 x 30 x 6 inches, and it weights close to 1.5 pounds.[9]

Deployment of a single DMSP satellite (illustrated in Figure 4) produces seven long-lived objects besides the satellite. Because all of these objects are released once the satellite has reached its final orbit, they will have lifetimes of 50-100 years, close to that of the satellite itself. The exact number of DMSP satellites to be launched is uncertain, because satellites are replaced as required. However, the planned number of launches of the Atlas booster with either a DMSP or a similar National Oceanic and Atmospheric Administration (NOAA) satellite is at a rate of two per year from 1988 to 1991.[9] Each additional launch continues to add to the amount of debris in near-Earth orbit. Table 2 lists the typical debris from a DMSP satellite launch.

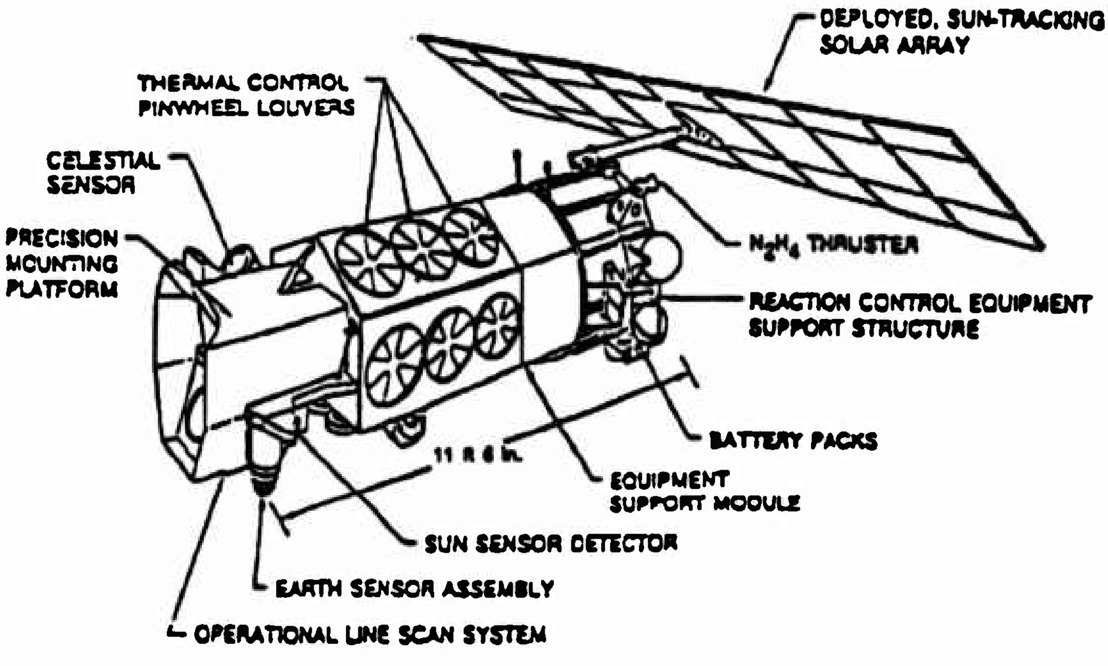

Figure 4. Defense Meteorological Satellite Program Spacecraft

[9] United States Air Force, Air Force Space Division (1988) *Position Paper on Man-Made Debris Hazards*, Air Force Space Division, Los Angeles Air Force Base, California.

Table 2. Typical Debris for a Defense Meteorological Support Program Satellite Deployment

DMSP	Number per Satellite	Size	Weight	Final Orbit	Expected Lifetime
Satellite	1	11 ft 6 inches 21 ft with solar array	1660 lb	450 nmi circular	50-100 yrs
Kick motor	1	N/A	N/A	450 nmi circular	50-100 yrs
Solar array bands	2	165 inches	0.75 lb	450 nmi circular	50-100 yrs
Retaining cord	2	18 inches	0.002 lb	450 nmi circular	50-100 yrs
Radiator cover	1	11 x 11 x 1 inches	0.5 lb	450 nmi circular	50-100 yrs
Optics cover	1	3 x 30 x 6 inches	1.3 lb	450 nmi circular	50-100 yrs

2.1.2 MID-EARTH ORBIT SATELLITES

Other launches into medium or geosynchronous orbits are similar to the DMSP satellite launches. Debris abatement policies have been implemented on the more modern systems and have reduced the number of small debris per launch. For example, a typical launch of the Navstar Global Positioning Satellite (GPS) (designed to provide very high accuracy three dimensional navigational information to the user) produces only two pieces of debris per satellite deployment when launched from a Delta II rocket. The Delta II second stage booster and the Payload Assist Module (PAM) booster are left in a 90 x 10,898 nmi orbit. A depletion burn is accomplished on the Delta II second stage to minimize the chance of explosion. Excess propellant is also burned off from the control system in the PAM booster to prevent explosion and the creation of additional debris. The second stage booster is expected to re-enter six months to a year after launch. The PAM booster is expected to re-enter the atmosphere after 3-5 years, depending mainly on the initial perigee altitude. The final apogee kick motor is retained inside the satellite.[9] Other debris abatement policies on GPS ensure that retaining pins and deployment systems are self contained and not released into space. Table 3 lists the debris from a GPS satellite launch.

There is, however, a major source of smaller but more numerous debris. This source of debris is the GPS PAM booster itself. The solid rocket propellant of the PAM booster creates a vast number of very small particles due to the incomplete combustion of the fuel. Millions of 0.001 to 0.1 mm sized aluminum oxide particles are released into orbit and add to the debris environment. The effect of these very small debris will be discussed in this section.

When the GPS system is fully operational in 1993 there will be 21 operational satellites and three on-orbit spares. The amount of debris 24 launches will produce will be significant.

Table 3. Debris Caused by the Deployment of the Global Positioning Satellite System

GPS	Number per Satellite	Size	Weight	Final Orbit	Expected Lifetime
Satellite	1	5 ft x 17.5 ft wth arrays	1855 lbs	10,898 nmi circular	>10000 yrs
Kick motor	0				
PAM-D	1	48 inches	345 lbs	90 x 10,898 nmi	3-5 yrs
Delta II Second Stage	1	N/A	N/A	LEO	6-12 months

2.1.3 GEOSYNCHRONOUS SATELLITES

An example of a geosynchronous satellite is the Defense Satellite Communication System (DSCS). The DSCS system is designed to provide global communications to the Department of Defense. During deployment of the DSCS system on an Atlas II/Centaur launch vehicle, the Centaur upperstage and the apogee kick motor are left as long-lived debris. Other launch associated debris either re-enters quickly (such as the payload fairing) or is captured or tethered.[9] The number of objects of debris per launch is not very high, but when you consider that there were more than 42 DSCS launches prior to 1987, the amount of debris adds up. The earlier satellite systems did not include debris mitigation processes in their designs. These older satellites released a number of retaining pins, straps, and blown off covers into orbit. Table 4 lists the debris from a typical DSCS satellite launch.

Table 4. Debris from a Signal Defense Satellite Communication System (DSCS) Satellite Deployment

DSCS	Number per Satellite	Size	Weight	Final Orbit	Expected Lifetime
Satellite	1	9 ft dia x 7 ft	2,581 lbs	geosynchronous	>10000 yrs
Centaur stage	1	10 ft dia x 30 ft	4,271 lbs	93 x 18,863 nmi	8-10 yrs
Apogee kick motor	1	114 in dia x 24 in	627 lbs	geosynchronous	>10000 yrs

2.1.4 SCIENTIFIC SATELLITES

The final example of current launches is a scientific satellite -- the combined Chemical Release and Radiation Exposure Satellite, otherwise known as CRRES. This satellite is a joint NASA/Air Force mission designed to study the effect of space radiation on advanced electronics and to investigate the Earth's magnetic field and the radiation it traps. During its mission CRRES will eject 24 chemical containers into a highly elliptical orbit. These 12 to 25 lb canisters will release their chemicals and become space debris. The Centaur booster that placed the CRRES satellite in its highly elliptical orbit was supposed to use the residual fuel to lower its perigee altitude, thus decreasing its lifetime. Unfortunately there was a failure of the booster systems after the satellite was released and the planned burn did not take place, leaving the booster in orbit. Table 5 lists the debris generated by the CRRES satellite launch.

Table 5. Chemical Release and Radiation Effects Satellite (CRRES) Debris Created During the Course of Its Mission

CRRES	Number per Satellite	Size	Weight	Final Orbit	Expected Lifetime
Satellite	1	6 ft dia x 6 ft 300 ft booms	2,000 lbs	204 x 18,863 nmi	>50 yrs
Centaur	1	10 ft dia x 30 ft	4,271 lbs	193 x 18,863 nmi	>50 yrs
Canisters					
Large	6	18 in dia x 24 in	25 lbs		>100 yrs
Small	18	9 in dia x 24 in	12 lbs		>100 yrs

2.2 The Increasing Number of Objects in Orbit

The number of manmade objects in orbit has increased rapidly since the early 1960's. There are now an estimated 70,000 objects 1 cm or larger and an estimated 3.5 million objects 1 mm or larger in Earth orbit. Of these objects, only 10 percent or about 7000 are large enough to be tracked and observed by the United States Space Surveillance System. The Space Surveillance System is discussed in detail in Section 5. The Space Surveillance Center maintains a catalog of all the space objects that are regularly observed with their array of sensors. The catalog includes the object's designation, origin, and orbital parameters. Due to limitations in equipment, the catalog contains only objects larger than 10 cm in diameter. Yet the Space Command Satellite Catalog still provides the best available record from which to deduce the increase in the amount of objects in space.

During the early 1960's there was a rapid increase in the number of space launches. The United States and the Soviet Union, being the only space powers at the time, were locked in a race to see who could utilize space during the height of the cold war. The number of launches has leveled since the early 1970's and has remained approximately 100 to 120 per year, as shown in Figure 5.

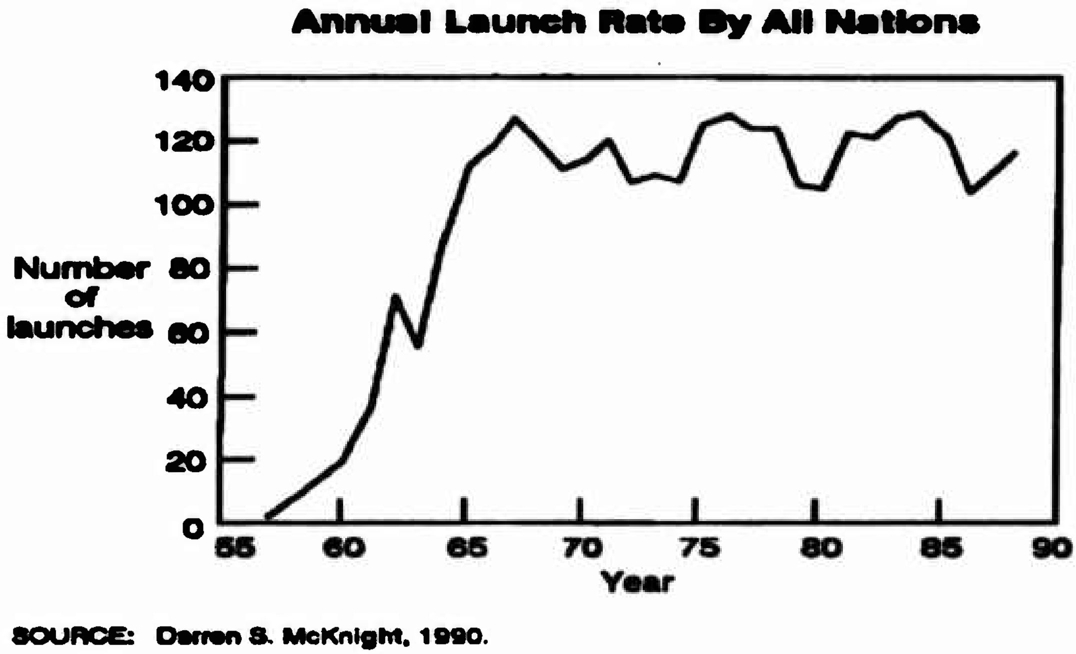

Figure 5. Annual Launch Rate by All Nations by Year[7]

While the number of launches has leveled since the rapid rise of the decade from 1958 to 1968, the number of cataloged objects has steadily increased at a rate of nearly 240 per year (Figure 6). This is due to longer life-time orbits and fragmentation of existing objects in orbit. Figure 6 shows the number of objects in the space command satellite catalog for each year from 1957 to 1989. Other lines on the chart show the number of objects in four different categories: payloads, rocket bodies, fragmentation debris and operational debris. These four categories will be discussed in detail later in this section. The number of additional objects in orbit that can not be observed by the Space Surveillance System is difficult to quantify because of the lack of data.

During certain years there was a rapid decrease in the number of objects in the catalog. This is due mainly to the effects of the 11 year solar cycle and the associated increase in atmospheric drag. Atmospheric drag serves as a cleansing mechanism for low-Earth orbit. The effects of atmospheric drag are covered in the last part of this section.

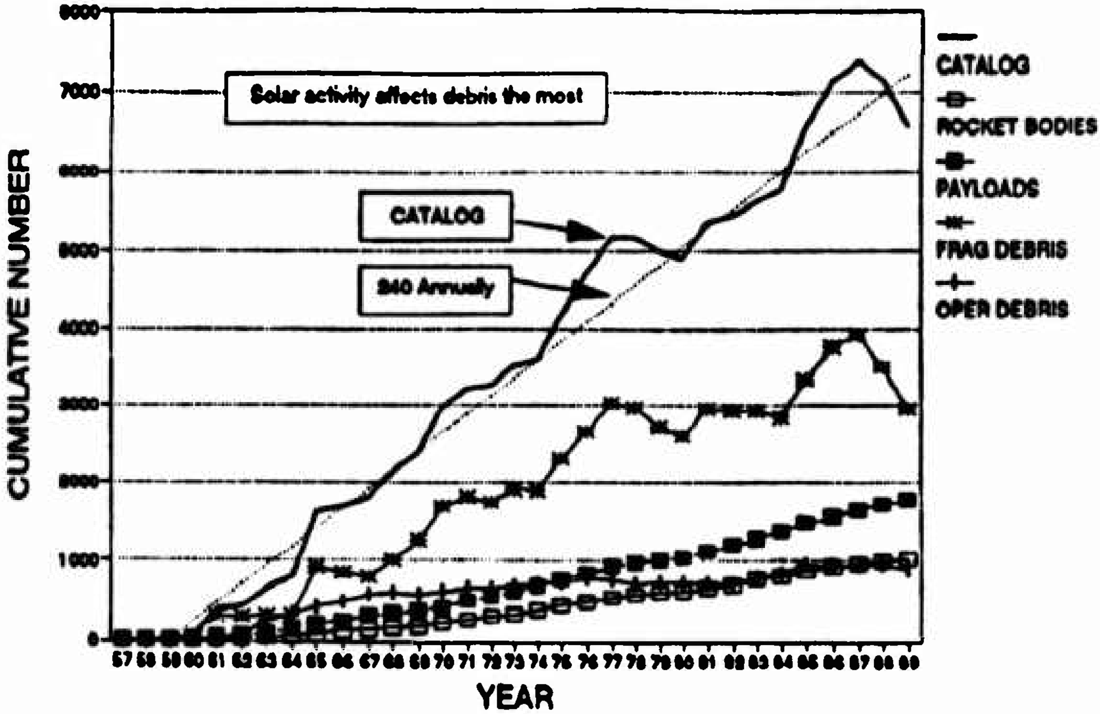

Figure 6. Number of Objects Contained in the Space Command Catalog by Category and Year[10]

2.3 Sources of Space Debris

The number of objects in orbit from each source can be approximated by using the satellite catalog. Fragmentation debris, the largest contributor, accounts for 45 percent of the trackable objects. Inactive payloads account for 16 percent, used rocket bodies account for 16 percent, and operational debris accounts for 12 percent. Operational satellites account for only 6 percent of all trackable objects.

Unfortunately this does not tell the entire story. Trackable debris is limited to objects on the order of ten centimeters or larger. These are the objects that the United States Space Command observes regularly and keeps track of their current orbital parameters. Many thousands of additional objects smaller than 10 cm are not included in this count. It is estimated that there are between 30,000-70,000 objects larger than 1 cm and 3.5 million objects larger than 1 mm in orbit.[2] Table 6 and Figure 7 show the breakout of the percentages from each source.

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[10] McKnight, D.S. and Johnson, N.L. (1990) Breakups and their effect on the catalog population, Article AIAA-90-1358 from the AIAA/NASA/DOD Orbital Debris Conference: Technical Issues & Future Directions, 16-19 April 1990, Baltimore, Maryland.

Table 6. Approximate Number of Objects in Earth Orbit by Category

Type of Object in Orbit	Approximate Number in Orbit	Percentage of Satellite Catalog
Operational Satellites	420	6
Inactive Payloads	1470	21
Operational Debris	840	12
Rocket Bodies	1120	16
Fragmentation Debris	3150	45
Untrackable Objects		
> 1 cm	30,000 - 70,000	
> 1 mm	3.5 Million	

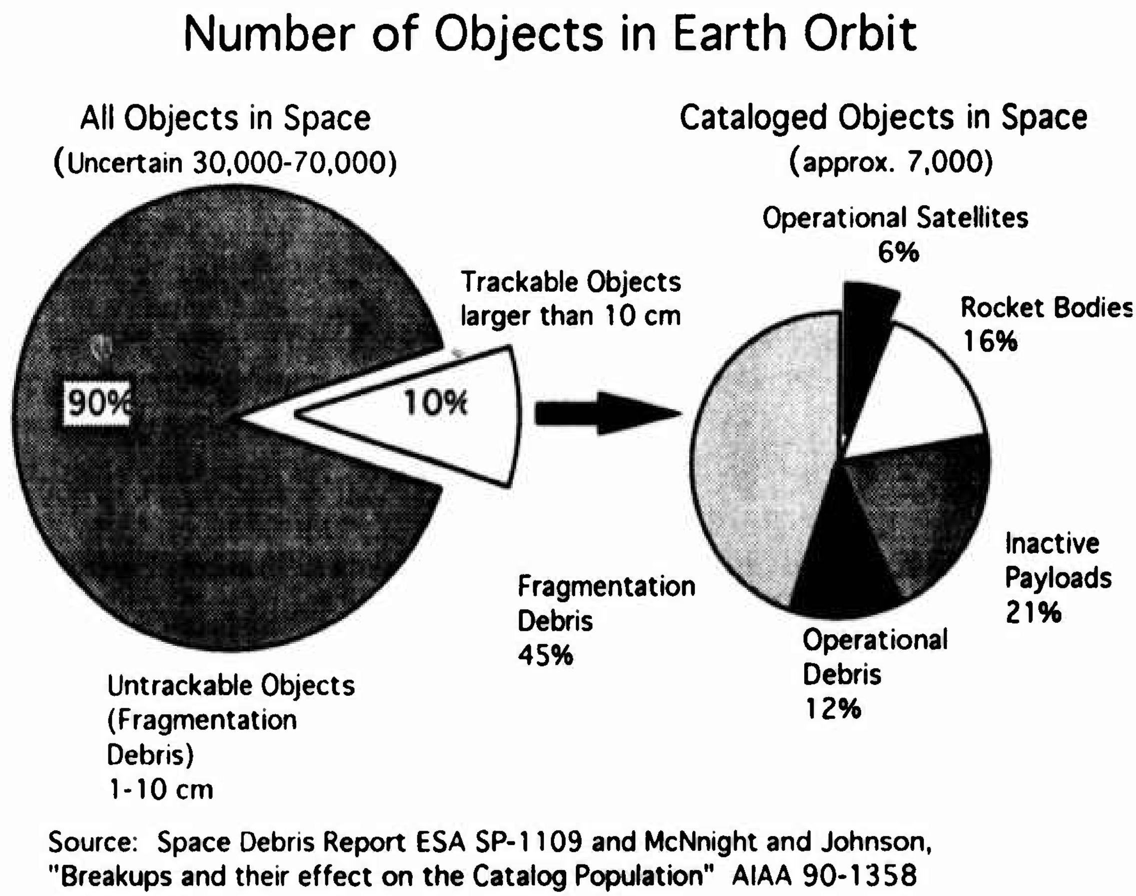

Figure 7. Break-out of Debris in Orbit

Looking at each of these categories individually will provide a greater understanding of the problem.

2.3.1 PAYLOADS

Payloads are the satellites, the experiments and the equipment used in any space activity. They provide the communications, the observations and the scientific data that justifies the expense of space flight. Payloads, however, eventually become another type of debris. Once they are out of fuel or deactivated, payloads for the most part are uncontrolled, useless space objects. There have been approximately 4000 payloads launched into orbit. Nearly 2000 payloads are still in orbit, but only 420 are operational. This leaves approximately 1580 old, discarded payloads in orbit. Most of the current operational payloads will remain in orbit for a long time, well exceeding their useful lives. Even the most modern geosynchronous communication satellites will last only 10 to 14 years. Satellites in geosynchronous orbit will remain in orbit forever unless removed by some means. A good example of inactive payloads are the second and sixth satellites launched by the United States, Vanguard I and Vanguard II. These satellites were launched by the United States in 1958. They are still in 3000 x 650 km orbits, where they will remain for the next few thousand years.

2.3.2 ROCKET BODIES

Nearly 50 percent of the total mass of debris on orbit consists of spent upper-stage rocket motors and tanks. These are left in orbit after they deliver their payloads to orbit. This is typical of most satellite launches. These boosters number over 1100 or 16 percent of the objects in orbit. These boosters and rocket bodies also provide the largest percentage of mass for another type of debris, fragmentation debris. Fragmentation occurs mainly when these discarded boosters explode due to a number of causes.

Rocket bodies and boosters are left in similar orbits as the payloads they deliver. This includes most orbits, including geosynchronous and geosynchronous transfer orbits. These tanks, boosters, and large payloads are the primary concern when discussing the Kessler effect -- one piece of debris colliding with another, thus forming more debris. This effect and its potential consequences are further discussed in a later section.

2.3.3 OPERATIONAL DEBRIS

Operational debris is created during the operation of deployment of space systems or experiments. Objects such as fairings, boosters, despin cables and weights are used during the deployment of spacecraft into orbit and are considered operational debris. Smaller operational debris such as bands, pieces of squibs and bolts are also often released. The solar-array cables and the covers released during the DMSP deployment discussed earlier are considered operational debris. For the first quarter of 1991, the average number of detectable debris created per successful satellite launch was close to three. The number of smaller debris produced is uncertain.

Operational debris has been limited in recent years by the implementation of debris abatement policies. However not all countries or companies are doing all that is possible to limit debris.

Scientific experiments have been known to cause a significant amount of operational debris. In order to collect the desired data or characterize some aspect of the space environment, objects are released in orbit. One notorious experiment which resulted in a significant amount of debris is known as the Westford Needles Experiment. In this 1963 communications experiment, researchers from Lincoln Laboratories in Massachusetts attempted to create an artificial ionosphere using thousands of small metallic needles in order to reflect radio signals.[11] These needles were to be placed in a high 2000 km X 5000 km near-polar orbit. The first experiment failed, but a second experiment succeeded in deploying the needles. To date Air Force Space Command has cataloged only 170 of these needles.[12] They are extremely difficult to track because of their small radar and optical cross sections. Several thousand additional needles are known to be in orbit. At these altitudes the needles will remain in orbit for at least several thousand years (because of the extremely limited atmospheric drag and their small surface area to mass ratio).

Other sources of operational debris are the objects accidentally released by astronauts while performing Extra Vehicular Activities (EVAs). During the Apollo and Gemini mission astronauts left a range of items in orbit, including a wrench. During a recent space shuttle mission an astronaut lost a watch. In the book *Diary of a Cosmonaut*, Valentin Lebedev describes the number of objects released to space when they opened the air lock to exit the Mir space station during an EVA. He said that "tiny glitter like dust flew away from the station. Space the gigantic vacuum cleaner, began to suck everything out of the station. Small bolts and screws lost long ago, drifted out along with dust from behind the compartment wall quilting; a pencil drifted out too."[13] While the amount of this unusual type of debris is limited, every object contributes to the danger of orbital collisions between space debris and operational spacecraft.

2.3.4 FRAGMENTATION DEBRIS

Fragmentation debris is the largest cause of orbital debris. Fragmentation debris is created when a spacecraft or booster, either intentionally or unintentionally, breaks up or explodes. To date there have been one hundred and four breakups. Some have resulted in little or no long-lived debris, while others have created hundreds of objects larger than 10 cm and perhaps tens of thousands of untrackable, smaller objects. This type of space debris accounts for 45 percent of the cataloged objects in space.

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[11] Christol, C. (1982) *The Modern International Law of Outer Space*. New York: Pergamon Press, Inc., p. 131.

[12] As of 1 July 1991, based on the Space Command Satellite Catalog

[13] Debris Chip - Diary of a Cosmonaut, *Orbital Debris Monitor*, 1 January 1991, pp. 5-6.

2.3.4.1 Causes of Orbital Breakups and Fragmentation

There are many causes of orbital breakups. Some are the result of deliberate actions, while some causes are still unknown. As of July 1990 deliberate causes accounted for 42 or 40 percent of all on orbit breakups. Propulsion related breakups are caused by failures in motors, tanks and engines in either rocket bodies or satellites. Typically the failure has been in tanks containing excess fuel that expands and ruptures the fuel tank. Propulsion related breakups accounted for 34 or 32 percent. Unknown causes accounted for 26 or 24 percent of all on orbit breakups. Other causes, such as electrical failure (one incident) and command problems (one occurrence), accounted for the remaining 2 percent.[14] These percentages are listed in Table 7 and their distribution illustrated in Figure 8.

Table 7. Percentage of Breakups Due to Different Causes

Cause of On-Orbit Breakups from 1961 to June 1991	Number	Percentage
Propulsion-Related	34	33%
Deliberate	42	40%
Unknown	26	25%
Electrical	1	1%
Command	1	1%

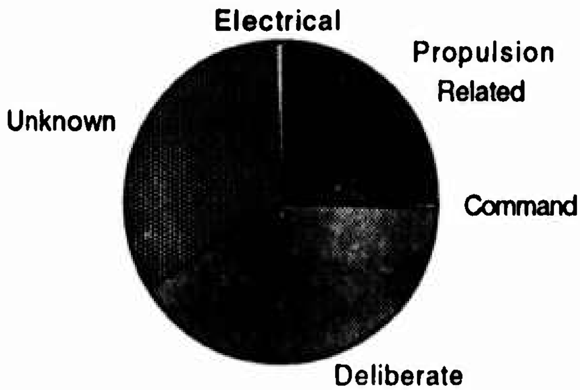

Figure 8. Percentage of Breakups Due to Different Causes

[14] Debris and Launch Watch - 1 July 1990, *Orbital Debris Monitor*, 1 July 1990.

2.3.4.1.1 Propulsion-Related Breakups

A large percentage of the breakups (33 percent) have been propulsion related, caused by residual fuel that detonates and destructs the satellite or booster. Breakups of this type were regularly observed with Delta II second stage boosters that detonated if the residual fuel was not vented after mission completion. Over-pressure caused the partition separating the hydrazine and the oxidizer to rupture which resulted in energetic explosion and detonation, fragmenting the booster. [15] At least eight Delta II second stages have exploded and created 1500 pieces of long lived debris large enough to be tracked. Heating of the tank in the sunlight caused an over-pressure of the tanks.

About 20 percent of all known debris is the result of rocket body breakups that occur after the rockets have successfully inserted their payloads into orbit.[16] By 1981, most U.S. boosters had been modified to eliminate this problem. NASA has developed a design program to prevent this type of event, and they are willing to share the information with anyone who is interested. The Soviets have taken similar steps. Despite these efforts, at least three breakup events of this type have occurred in the past year: an Ariane Booster detonated while placing a French SPOT imaging spacecraft in a 900 km sun-synchronous orbit; a Chinese Long March booster exploded after placing a satellite in a similar sun-synchronous orbit; and an Atlas second stage booster that had placed a satellite in orbit in 1975 exploded last year.

2.3.4.1.2 Deliberate Breakups

Deliberate acts are the leading cause of satellite breakups. To date 40 breakups in orbit have been initiated deliberately. There are two major sources of deliberate breakups -- anti-satellite tests (12 occurrences) and Soviet Cosmos explosions (14 occurrences). The Soviets have typically destroyed their reconnaissance satellites after they have completed their useful lives to keep the US from learning about their capabilities by using advanced optical systems to image older satellites. Another major source of breakups has been anti-satellite tests conducted by both the US (2 tests) and the USSR (10 tests). These deliberate explosions are considered high-intensity explosions. Propulsion related explosions are considered to be a lower intensity than deliberate explosions. These high-intensity explosions produce more small, untrackable debris in the 1 mm to 10 cm range.[2]

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[15] Kaman Sciences Corporation (1991) *An Assessment of Recent Satellite Breakups on the Near-Earth Environment*, Kaman Sciences Corporation, Alexandria, Virginia.

[16] Johnson, Nicholas (1991) Teledyne Brown Engineering, The Fragmentation of the Fengyun 1-2 Rocket Body (TBE CS90-TR-JSC-013), *Orbital Debris Monitor*, 1 January 1991.

2.3.4.1.2.1 Anti-Satellite Tests

Some causes of fragmentation are the result of anti-satellite (ASAT) tests conducted both by the United States and the Soviet Union. A total of twelve breakups have been attributed to the testing of anti-satellite weapons. This in turn accounts for 7 percent of the current catalog population.[7] The results are given in Table 8.

The Soviet anti-satellite concept places an interceptor satellite in an orbit close to that of the target satellite. It then maneuvers close to the target satellite. As the interceptor approaches the target, a conventional warhead explodes sending hundreds or perhaps thousands of small millimeter-sized pellets, similar to BBs or buckshot, that spray the target satellite, destroying it. The Soviets ran ten such ASAT tests that included satellite breakups. It is unclear how many anti-satellite weapons were loaded with the smaller fragments that actually accomplish the destruction of another satellite.

The United States' anti-satellite concept relies on a more accurate interceptor that actually collides with the target spacecraft. These hypervelocity impacts create large amounts of untrackable debris. The European Space Agency estimates that hypervelocity impacts create 10 times more debris than an explosion event. It estimates that a collision with a 3000 kg spacecraft will create 30,000 particles over 1 gram where an explosion will create approximately 3,000.[2] During the test of the US air launched anti-satellite weapon, a small interceptor collided with the P-78 Solar Wind satellite. The collision occurred at very high relative velocity (over 6 km/sec) and created 285 objects large enough to be cataloged. It is expected that several thousand smaller, non-catalogable objects were also created at the same time and are still in orbit.

During the other United States test, the Delta 180 Strategic Defense Initiative experiment, two objects collided in orbit, creating 381 objects that were detected. Of the 381 objects, only 18 were cataloged because most of the debris re-entered quickly due to the low altitude of the experiment.[7]

The testing of anti-satellite weapons has caused a significant amount of orbital debris. Much of this debris is still in orbit and it now threatens operational space systems.

Table 8. Space Weapons Tests[7]

Class of Breakup	Number of Events	Number of Objects Cataloged	Number of Objects Remaining in Orbit
Phase 1			
Soviet ASAT	7	545	296
Phase 2			
Soviet ASAT	3	189	154
US ASAT			
P-78 Breakup	1	285	38
Delta 180 Experiment	1	18	0
	12	1,037	488

2.3.4.1.3 Unknown Causes

The third largest group of satellite breakups falls into the category of unknown. These unexplained breakups total 26. Many of the breakups probably fall into the propulsion or deliberate categories but have not been classified as such due to a lack of data. There is a chance that some of these breakups may be the result of collisions with debris. According to the European Space Agency's statistical analysis, the present density of debris is large enough to have caused collisions. The leading candidate for a hypervelocity collision with debris is the Cosmos 1275 fragmentation in 1981 that created 281 observable pieces.[2] The velocity spread of the debris from the breakup approximates what scientists expect from an on-orbit collision.

2.3.4.1.4 Other Causes

Other known causes of fragmentation debris have caused on-orbit breakups. One satellite was fragmented due to an electrical problem, and another was fragmented by an anomalous command sent from a ground station.

Fragmentation debris is by far the most dangerous type of debris. Larger debris (> 10 cm) is detectable and, theoretically at least, avoidable. The effect of smaller debris (< 1 mm) can be minimized by satellite design and shielding. But much of the fragmentation debris falls between these two limits.

To avoid satellite collisions with large debris, Space Command can determine the future position of space objects and provide advance warning of a possible collision between cataloged objects. But for advance warning to be provided, the debris must be large enough to be detected by the Space Surveillance System. This fact will be addressed in Section 7 in the discussion of debris mitigation efforts since it is not currently possible to track debris smaller than 10 cm and because of this no warning of possible collision is available. The capabilities and limitations of the Space Surveillance Network, the system used by United States Space Command to track space objects, is discussed in Section 5. Currently a majority of the small fragmentation debris is not trackable. Yet because of its high velocity, small debris can cause significant damage to even well-shielded spacecraft. The risks of damage caused by space debris is covered in detail in Section 4.

Fragmentation debris consists mainly of aluminum, steel, titanium and other substances used in designing rockets, satellites, and other space systems. Most of these are dense materials, so the atmospheric drag has a lesser effect than it would on less dense paint chips or exhaust particles. The denser materials also have a higher penetrating ability that makes them more dangerous, even to shielded systems such as the future Space Station.

2.3.4.2 Breakup Modeling

One of the reasons for the wide range of estimates for the number of objects in orbitis that the dynamics of breakup is not well understood, and no one is sure how many undetectable particles the fragmentation of a satellite creates. Actual ground-based tests have been conducted in an attempt to quantify the amount of debris caused by an orbital breakup of a satellite or booster.

One test used an Atlas missile that was purposely exploded. Almost all the mass went into fragments 10 cm or larger. Only a small percentage of the booster broke into 1 mm to 1 cm fragments. The other test performed by Physical Sciences, Inc in Massachusetts, showed a significantly larger proportion of the fragments falling between 1 mm and 1 cm.[17] Figure 9 shows the results of these tests for a sample satellite of 1400 kg. It also shows the amount of debris that would be created if all the mass were concentrated in a single size of fragments. The Physical Science, Inc data has been scaled to represent the sample satellite.

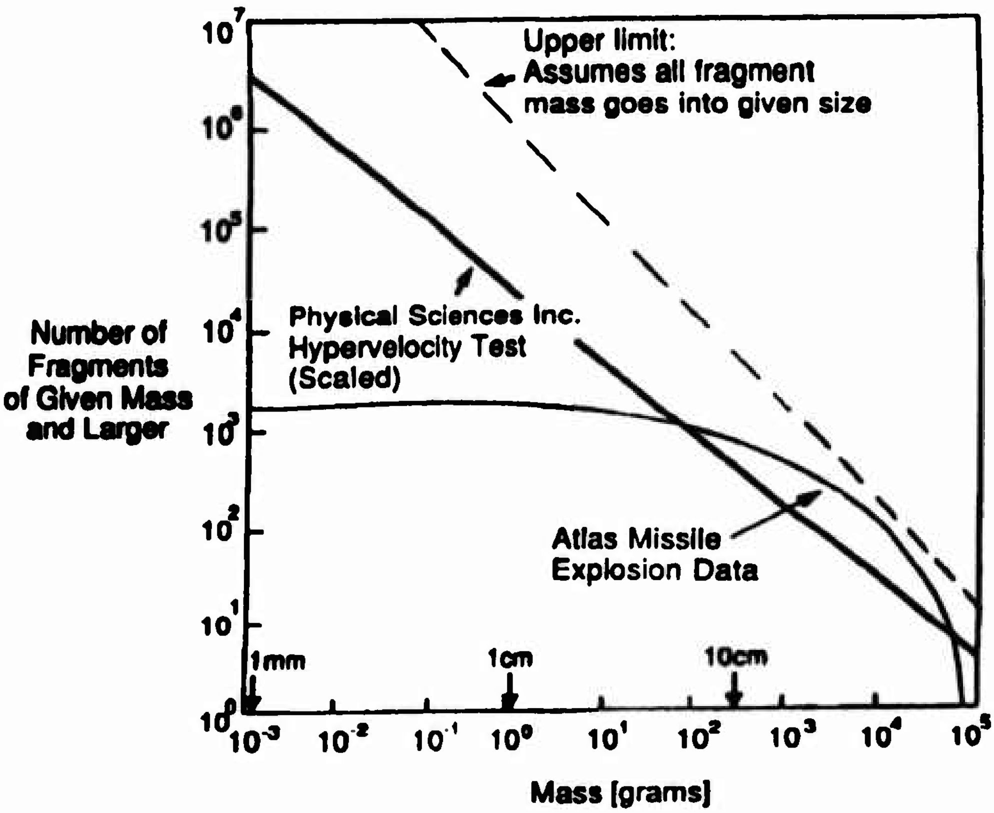

Figure 9. Expected Number of Fragments per Mass of a 1400 kg Satellite Based on Fragmentation Test Results[17]

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[17] Kessler, Donald J. (1991) Orbital debris environment for spacecraft in low earth orbit, *Journal of Spacecraft and Rockets*, May - June 1991, pp. 347 - 351.

2.3.4.2.1 Orbital Characteristics of Fragmentation Debris

When satellites break up they form a cloud of debris. The rate of expansion of this debris depends on the amount of energy released during the breakup. Some energetic breakups can impart velocities of several hundreds of meters per second in addition to the original orbital velocity. The energetic breakup of the Delta II booster on 1 May 1991, imparted enough velocity to the fragments to cause a 1 to 2 degree change in inclination. It also provided the velocity required for some pieces to change their apogee altitudes from the original 1100 km to 3500 km.[18] These differences in velocity cause the cloud of debris to disperse over time and can cause significant differences in orbital period and inclination. Figure 10 graphically shows the velocity imparted during an explosion.

The initial velocity distribution is the least developed component of the existing breakup models. The imparted velocity range on the debris depends largely on the type of fragmentation that occurs. Explosions can impart velocities 100 to 600 m/sec on fragments.

Initially, any type of fragmentation creates a dense cloud of debris as shown in Figure 11(a).[7] Because of the differences in imparted velocity, some debris is thrown into higher orbits, some into lower orbits. Objects in higher orbits have a longer period of revolution, and hence they fall behind the faster, lower altitude objects. The initial cloud eventually spreads over the entire orbit due to differences in the periods caused by the impulse provided by the explosion. This is shown in Figure 11(b). Debris will also spread over a narrow band, 1-3 degrees, of inclination. The effect of the oblateness of the Earth (J2) causes the plane of the orbit to rotate around the Earth's polar axis in the direction opposite the motion of the satellite. This phenomenon is known as the regression of the node. [Reference 19 p. 504] This will cause the line of ascending node, the point where the object passes the equator going north, to change for objects at a different rates for different inclinations. Figure 12 shows the orbital angles discussed for a satellite and debris.

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[18] Delta Second Stage Break Up, *Orbital Debris Monitor*, 1 July 1991, p. 7.

[19] Battin, Richard (1987) *An Introduction to the Mathematics and Methods of Astrodynamics*, New York: American Institute of Aeronautics and Astronautics, Inc.

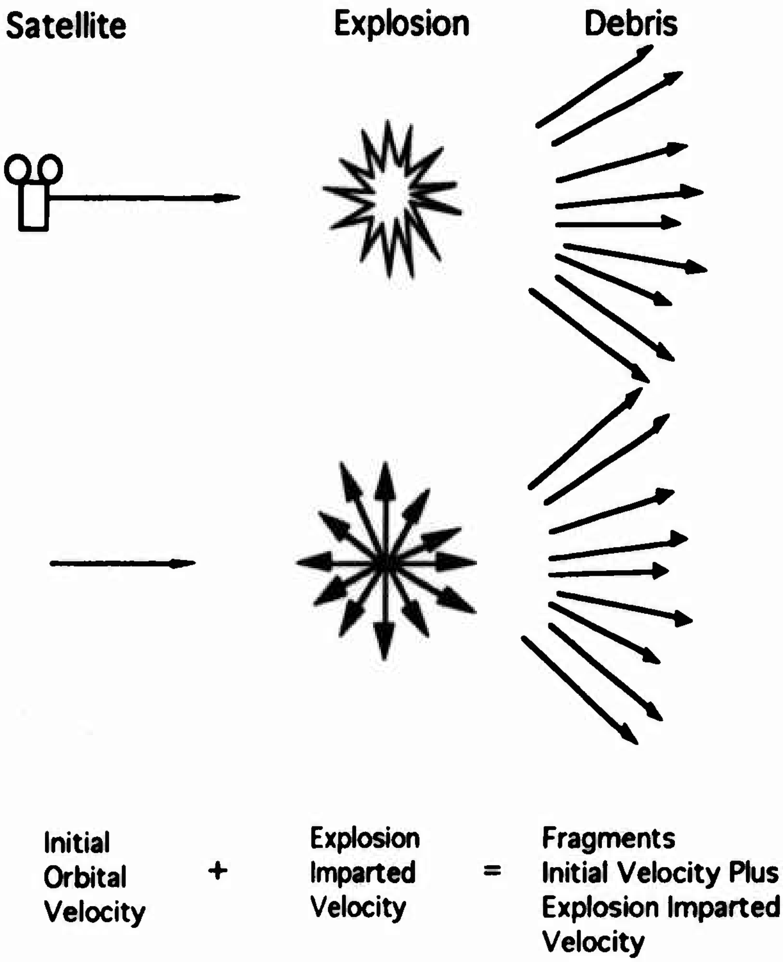
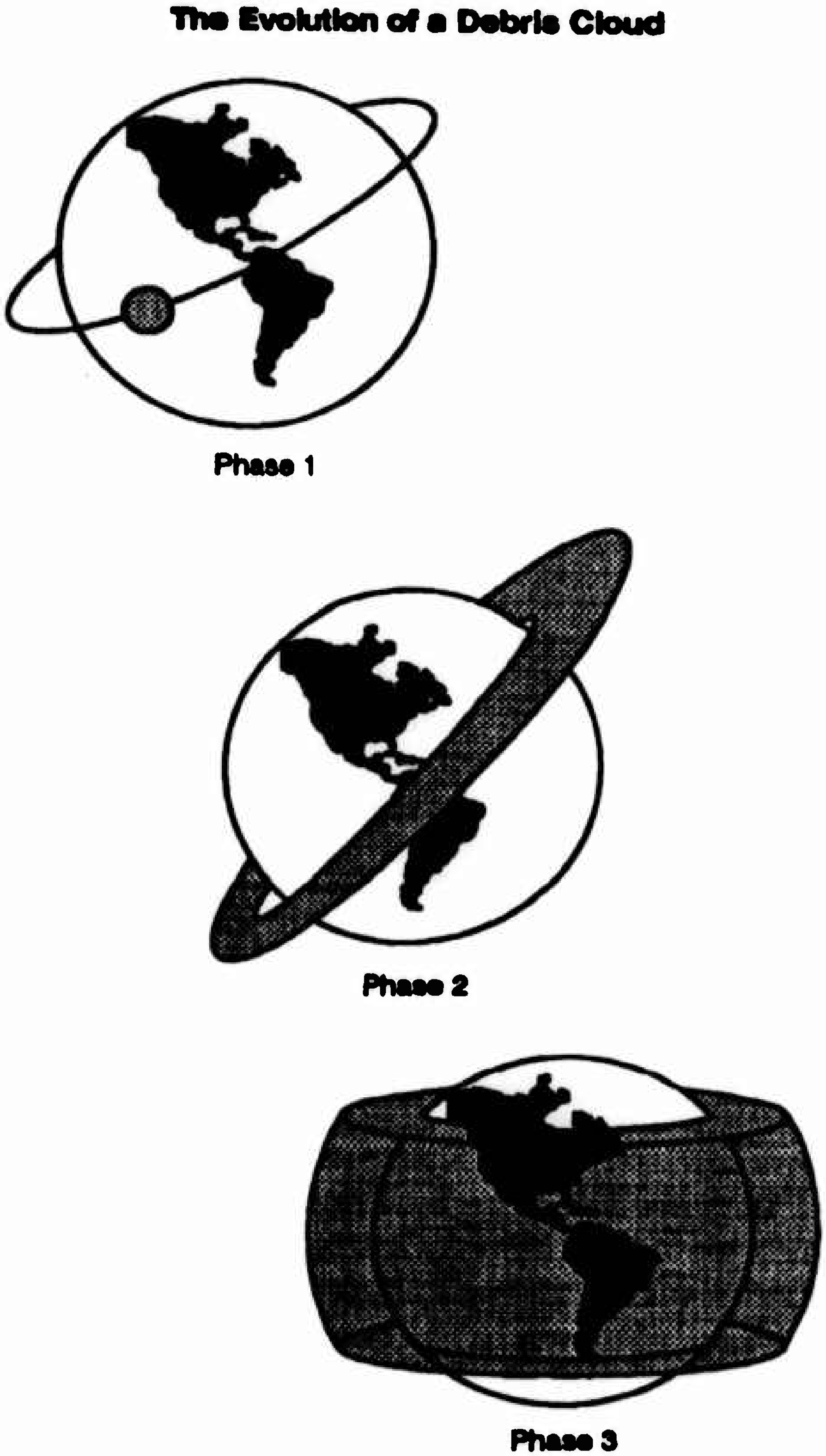


Figure 10. Imparted Velocity on Debris During Breakup



Figures 11 a,b,c. Evolution of a Debris Cloud Over Time

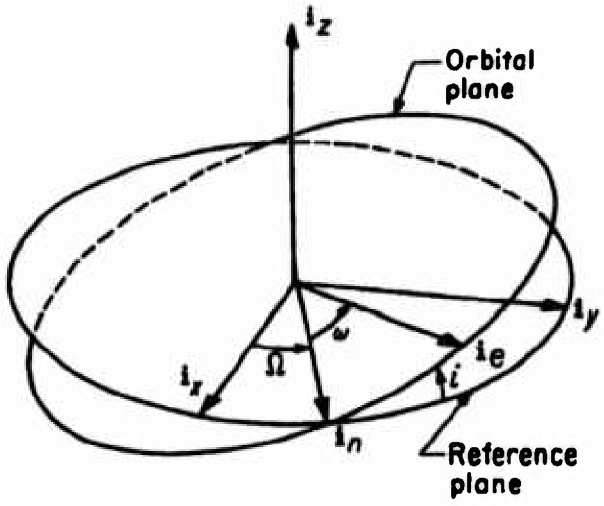


Figure 12. Orbital Elements [Reference 19, p. 124]

Ix, Iy, and Iz are unit vectors forming a right hand coordinate system. Ix is in the direction of the vernal equinox. In is in the direction of the ascending node. Ie is in the direction of the perigee. Ω is the longitude of the ascending node and is the angle between Ix and In. ω is the argument of periapsis.

The rate that the longitude of the ascending node changes for any particular piece of debris is given by Eq. (1).

$$\frac{\overline{d\Omega}}{dt} = -9.96\left(\frac{R_{eq}}{a}\right)^{3.5}\left(1-e^2\right)^{-2}\left(5\cos^2 i\right) \text{ degrees/day} \tag{1}$$

where R_{eq} is the equatorial radius of the Earth, a is half of the sum of the apogee and perigee altitude as measured from the center of the Earth, e is the eccentricity, and i is the inclination.

Not only will the debris spread around the globe, but it will also change the argument of periapsis, the angle from the equatorial plane to the perigee point measured along the orbit. The average rate of rotation of the line of apsides, the line from the center of the Earth to the location of perigee, is also dependent on the inclination and is given by Eq. (2). [Reference 19, p. 504]

$$\frac{\overline{d\omega}}{dt} = 5\left(\frac{R_{eq}}{a}\right)^{3.5}\left(1-e^2\right)^{-2}\left(5\cos^2 i-1\right) \text{ degrees/day} \tag{2}$$

Over time, the effect of the difference in inclination and period plus the effect of the oblateness of the Earth (J2) will cause the debris to spread over all right ascensions. Eventually this precession will spread the debris over a torus around the Earth as shown in Figure 13.

2.3.4.3 Breakup Example - OMICRON 1961

On 29 June 1961, less than four years into the Space Age, the first occurrence of what would become the major cause of orbital debris took place. On its first revolution around the Earth, a Transit 4A payload and the Ablestar rocket that propelled it into orbit, exploded into several hundred pieces. Post-event analysis determined that either a propulsion-related explosion or activation of the range safety explosive system caused the explosion.[20] This breakup is known as the 1961-Omicron event and has been an oft-cited example to demonstrate the effects of satellite fragmentation.

As of January 1991 a total of 297 trackable pieces of Transit 4A had been cataloged. Approximately 230 trackable objects remain in orbits that range from highly elliptical 2000 km x 400 km orbits to near circular 900 km orbits.[1] The wide spread of altitudes that is covered is due to the energy released during the breakup. In addition to these trackable pieces, hundreds or perhaps thousands of objects too small to be tracked remain in orbit. The majority of all the pieces from the Omicron breakup are expected to remain in orbit for over 100 years.[20] Figure 13 shows the Ablestar rocket body and the resulting debris traces from the 1961 Omicron breakup. The traces in Figure 13 are viewed looking down on the North Pole.

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[20] Breakup in Review: 1961 Omicron, *Orbital Debris Monitor*, 1 April 1988, p. 10

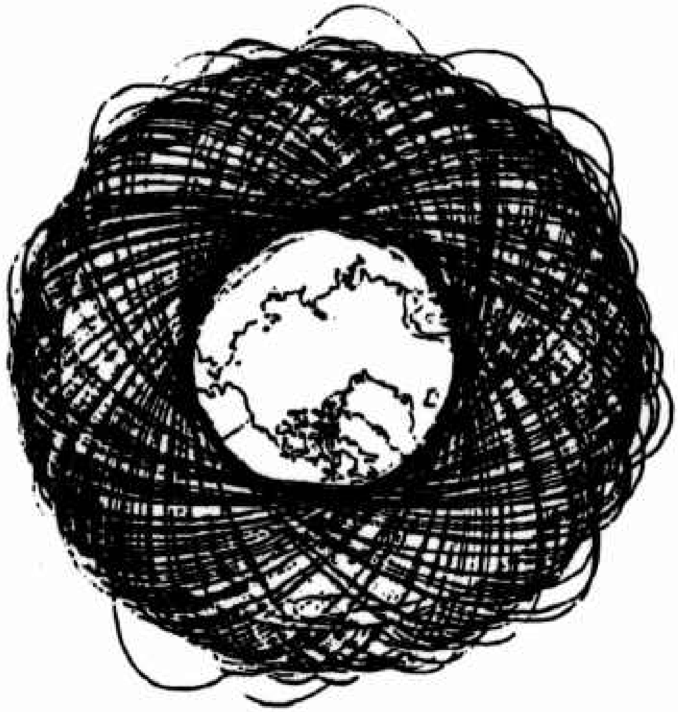

Figure 13. The Resulting Debris Cloud from the Omicron Break Up as Seen Looking Down on the North Pole[20]

While the Omicron breakup was both the first orbital breakup and perhaps the worst, it was by no means the last. Since 1961 there have been 104 orbital breakups, with as many as eight occurring in the first half of 1991.

2.4 Smaller Debris Sources

In addition to the sources of debris previously discussed, there are smaller particles that present different dangers to space operations. These types of debris do not appear in the satellite catalog because it is not currently possible to detect or track them. Small debris is known to be created by chipped paint from operational satellites. Even smaller debris comes from the exhaust of solid rocket motors. While these types of debris are not as dangerous as the larger debris, they still pose significant hazards to Extra Vehicular Activities (EVAs), such as those required for the Space Station Freedom. Other problems include the erosion of optical surfaces, insulators, or connections on solar arrays. The extent of this type of small debris is very uncertain because of a lack of data.

2.4.1 PAINT CHIPS

Paint chips are generated by a number of mechanisms. Paint is used to control the thermal properties of spacecraft. As the spacecraft ages, paint begins to flake off. This is caused by a number of factors, the primary one being the effects of the sun and thermal expansion and contraction. All satellites in low earth orbit (except some sun-synchronous orbits) constantly move between sunlight and darkness. As the spacecraft changes temperature, it expands and contracts. If the paint does not have the same thermal expansion coefficient, it begins to crack and flake off. This effect is aided by the effects of atomic oxygen and ultraviolet radiation which can degrade the paint over time from its original characteristics. Paint chips can also be displaced by micrometeors and small pieces of debris. Modern spacecraft paints are designed to overcome many of these flaking problems, but there are many older, non-operating satellites still in orbit that used older paints which will begin to flake, if they haven't already done so.

Paint flecks do not have a high mass to area ratio so they will be relatively short-lived in low-Earth orbits as compared to other forms of debris. However paint chips in medium, or geosynchronous orbits encounter very low or no atmospheric drag, so the particles will pose a threat for a long time to come. To give an example of the types of effects small paint chips can have, during the Space Shuttle Mission STS-7, a small 0.2 mm paint fleck impacted the shuttle side window. Although it did not puncture the window, it did require $50,000 in repairs. [Reference 6, p. 15]

2.4.2 EXHAUST PARTICLES

Solid rocket exhaust particles range from 0.001 to 10 micrometers in diameter. They are formed by the incomplete burning of the propellent in solid rocket upper stages during orbital insertion or orbital boost maneuvers.[21] Two such US solid rocket boosters are the Payload Assist Module and the Inertial Upper Stage. Large exhaust particles can easily be seen during launch of sounding rockets, and similar particles are produced by upper stage boosters. Exhaust particles can have a variety of lifetimes in orbit depending on the orbital parameters and operation during boost. Particles from rockets used to insert a geosynchronous satellite into orbit will remain there for six months to several years, depending on their size and orbital parameters.[21] Those used to inject a satellite into a circular low-Earth orbit will return to Earth rather rapidly. These particles have a low mass to surface area ratio and are affected strongly by atmospheric drag and solar radiation pressure. A 500 kg motor used to place a 1000 kg satellite in geosynchronous orbit will produce approximately six million particles larger than 30 micrometers, 2 billion larger than 20 micrometers and 2 trillion larger than 10 micrometers.[21]

The effect of collisions with these particles is similar to the effect of sandblasting. Surfaces erode and degrade slowly over time as pits and small craters are formed. While not critical to most structural components, optical components such as mirrors and lenses are placed at risk. This

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[21] Akiba, R., Ishi, N., and Inatani,Y. (1990) Behavior of alumina particle exhausted by solid rocket motors, Article AIAA-90-1367 from the AIAA/NASA/DOD Orbital Debris Conference: Technical Issues & Future Directions, 16-19 April 1990, Baltimore, Maryland.

effect on optical components could play a key role in the development of optical surveillance systems for SDI where a long term capability is required. Design of space based high energy laser systems or relay mirrors must account for effects caused by this type of debris damage. Small pits or damage to optical coating under proposed high energy laser systems (such as Zenith Star) will render a mirror useless because the mirror could absorb too much energy and melt or shatter.

Other effects that could damage all satellites include erosion of painted surfaces and degradation of photo-voltaic cells. Connections on the solar arrays can be damaged, decreasing their performance.

2.4.3 NATURAL DEBRIS AND METEORS

Space debris is a manmade hazard. There are other types of natural hazards such as meteors that pose a similar threat. Asteroids have cratered the Earth, the Moon, and all other celestial bodies. An accepted estimate of the mass of meteors within 2000 km of Earth is 200 kg.[22] These meteors are on hyperbolic trajectories and move very quickly through the space near Earth. Meteors can be rocks, dust, or ice. Typical velocities of meteors are above 20 km/sec. At these velocities, most micrometeors vaporize on contact and do not cause significant structural damage.

Although space debris was not a large concern to the earliest space systems, it was a concern to the Apollo program in the 1960's. During the Apollo program, design considerations were made to ensure the command module and the lunar lander could withstand a collision with micro-meteors up to 0.3 mm in diameter.[23] Since then, the threat of collisions with manmade objects in low-Earth orbit has far exceeded the threat of collisions with natural meteors.

2.5 Responsibility for the Growth of Space Debris

Historically, the US and the USSR have been the major space powers. One would expect that since the Soviet Union accounts for nearly 70 percent of all space launches, it would account for a majority of the space debris. This, however, is not the case. The Soviet Union and the United States are nearly equally responsible for the number of objects in orbit. The Soviets have tended to use short lived low-Earth orbits for their military satellites. This has been because of their relatively short missions. A benefit of this has been a reduction in the amount of long-lived space debris they have produced. The United States has tended to use higher orbits, which are practical for longer-duration satellites. This has led to a longer-lived debris population per launch.

At this time the US and the USSR account for nearly 93 percent of all cataloged objects. However, this is rapidly changing as other countries such as the European Community, China, and Japan enter the space launch business. Figure 14 shows the present tally of objects in orbit.

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22 Chobotov, V.A. *The Space Debris Problem and Preliminary LDEF Results*, California: the Aerospace Corporation.

23 Kessler, Donald J. (1991) Orbital debris project overview, briefing presented on 22 November 1991.

Both the Europeans and the Chinese have suffered fragmentation events that have significantly added to the debris population. The European Space Agency lost a Spot satellite and a Viking Rocket in sun-synchronous 800 km orbit forming over 500 objects large enough to be tracked by the Space Surveillance Network. On 4 October 1990 a Chinese rocket booster fragmented, producing 81 long-lived trackable objects in a 900 km sun synchronous orbit. The actual cause of the breakup of the Chinese rocket is unknown, but the leading candidate is a propellant-induced explosion.[24]

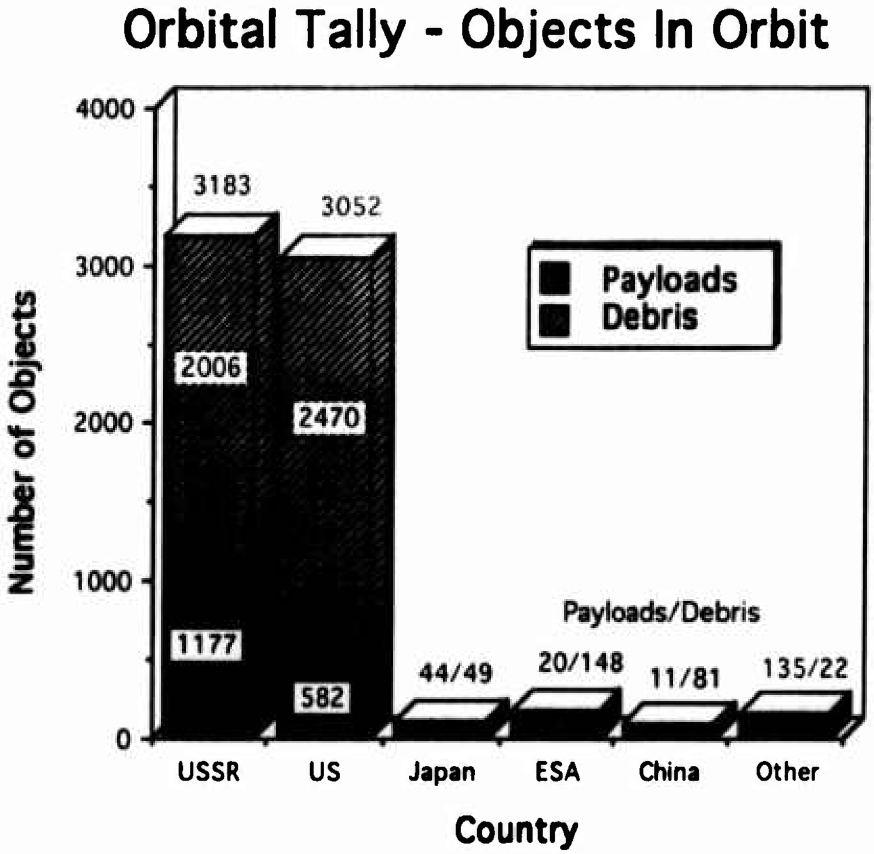

Figure 14. Orbital Tally Current Number of Objects in Orbit by Country Payloads/Debris

2.6 Natural Debris Removal Mechanism

The only natural method for removing objects from orbit is for them to re-enter the Earth's atmosphere. Atmospheric drag is the primary cleansing mechanism for low-Earth orbit. All objects

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[24] Break up in Review - Fengyun 1-2 R/B, *Orbital Debris Monitor*, 1 January 1991, p. 6.

below 1000 kilometers are affected by atmospheric drag. As objects are affected by atmospheric drag they come closer to the Earth where they experience even more drag. These objects eventually spiral in and burn up in the atmosphere. Debris above 1000 km experiences little to no effect from the atmosphere. These high altitude objects continue in their orbits, mostly unaffected by the atmosphere.

The effect of small changes in atmospheric drag can be seen in the correlation of the number of objects in space and the solar cycle. At the peak of the 11 year solar cycle, the sun is more active and emits slightly more radiation. This causes increased heating of the Earth's atmosphere, causing it to expand outward. This results in increased drag that decreases the orbital lifetime of objects in low-Earth orbit. During this period a larger amount of debris and satellites re-enter the Earth's atmosphere. Figure 15 shows the average lifetime of circular orbits as a function of altitude at the maximum and minimum levels of solar activity. Figure 16 shows the corresponding solar activity and the number of objects in orbit. Increased solar activity was blamed for causing the United States' only orbiting laboratory, Skylab, to re-enter before NASA could boost it to a higher, safer orbit.

Other forces on orbiting objects are the gravitational pull of the sun and the moon, as well as solar radiation pressure. Objects in highly elliptical orbits are significantly affected by these three forces. These forces, although slight, can change an orbit enough to lower the altitude to the point that atmospheric drag forces will cause them to spiral down and re-enter the atmosphere. Solar pressure is the dominant perturbing force on high altitude, low density, high surface area objects. These objects include paint flecks and exhaust particles.

There are no removal mechanisms for high altitude circular orbits. Large objects in geosynchronous orbit will remain in orbit until they are actively removed.

2.7 The Kessler Effect and Self-Generating Debris

The Kessler Effect is the worst case scenario of the debris problem. It describes the effects of random collisions between objects in orbit which produce debris faster than the natural removal mechanisms can remove it. The probability of occurrence of the Kessler Effect increases with time due to an ever increasing number of objects in orbit. Large objects, such as boosters and used satellites, have large masses that can be fragmented through collisions into thousands of smaller debris. The effects of the atmosphere at higher altitudes are not strong enough to remove such objects fast enough to avoid a chain-reaction with an increasing number of objects resulting in a higher rate of collisions. The result would be a runaway self-generating debris population that can render certain altitude regions unusable for space activities.

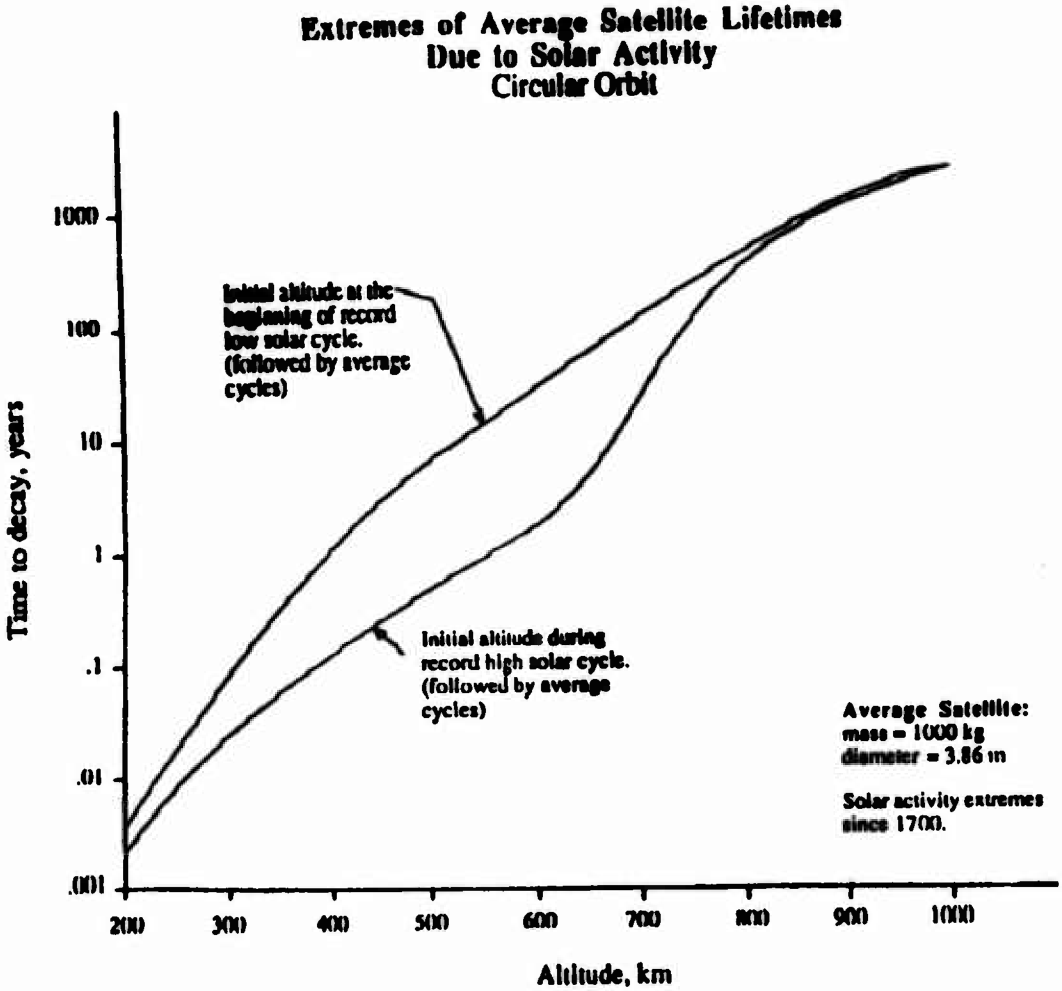

Figure 15. Circular Orbit Lifetimes at Maximum and Minimum Solar Activity[25]

The Kessler Effect defines a critical density of debris beyond which the generation of debris from random collisions produces debris at a faster rate than the natural rate of their removal at a given altitude. Once the critical density is reached, the debris population will increase even without any additional objects being placed into orbit.[26] To determine the critical density only objects 10 cm or larger are considered because they have enough kinetic energy to shatter large objects.

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[25] Kessler, Donald J. (1991) Orbital debris models at JSC, Phillips Laboratory, NASA and Aerospace, briefing presented at the Orbital Debris Technical Interchange Meeting, 2-3 April 1991.

[26] Kessler, Donald J. (1991) Collisional Cascading: The Limits of Population Growth in Low Earth Orbit, NASA/Johnson Space Center, Houston, Texas, Paper No. MB.2.2.2 presented at the XXVIII COSPAR Meeting, The Hague, Netherlands, *Advances in Space Research*, **11** (No. 12):63-66

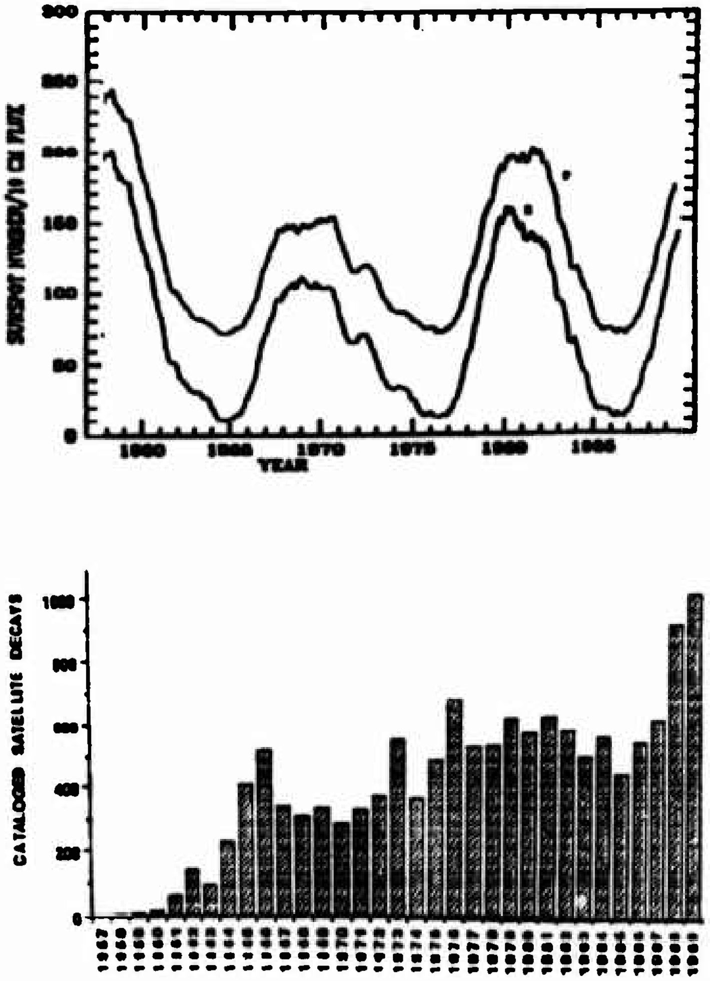

Figure 16 a, b.

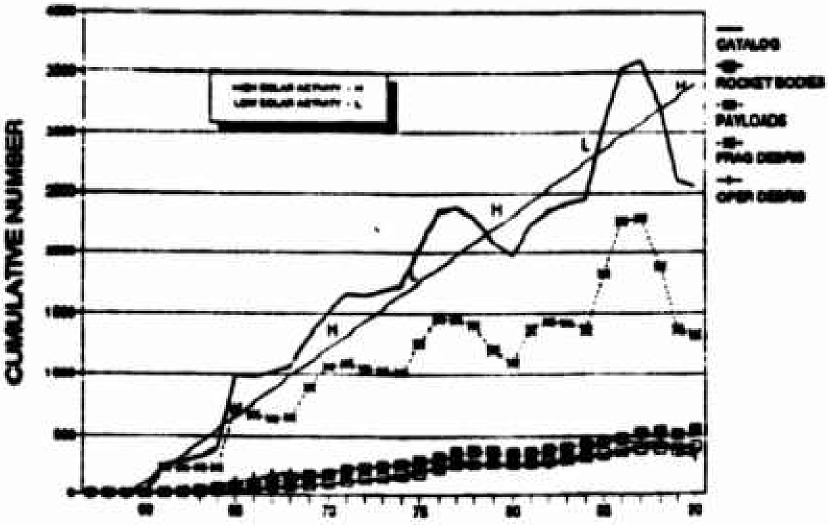

Figure 16 a,b,c. a) Solar Activity Measured by the Sunspot Number (bottom line) and F10 Index (top line), b) The Number of Decaying Cataloged Objects by Year, and c) the Total Number of Low Earth Orbiting Objects below 1000 km Contained in the Satellite Catalog by Year

There is evidence that the critical mass and number of objects that would induce unstable debris population growth has already been exceeded in some altitude regions. Figure 17 shows the critical density and the orbital population at various altitudes corrected for inclination and size distributions as reported by Kessler.[26] It shows that the critical density has already been exceeded in the altitude region around 1000 km and 1400 km. A large population of uncataloged objects would widen the the unstable regions in orbit.

While the level of debris that induces the onset of the Kessler Effect is in doubt, the fact that the effect can occur is well accepted, since the rate that objects are expected to break up due to random collisions is a function of the rate of increase of the number of objects in orbit. Figure 18 shows the rate that large objects such as payloads or expended rocket bodies will break up due to collisions at different levels of space launch activities as predicted by the Kessler Effect.

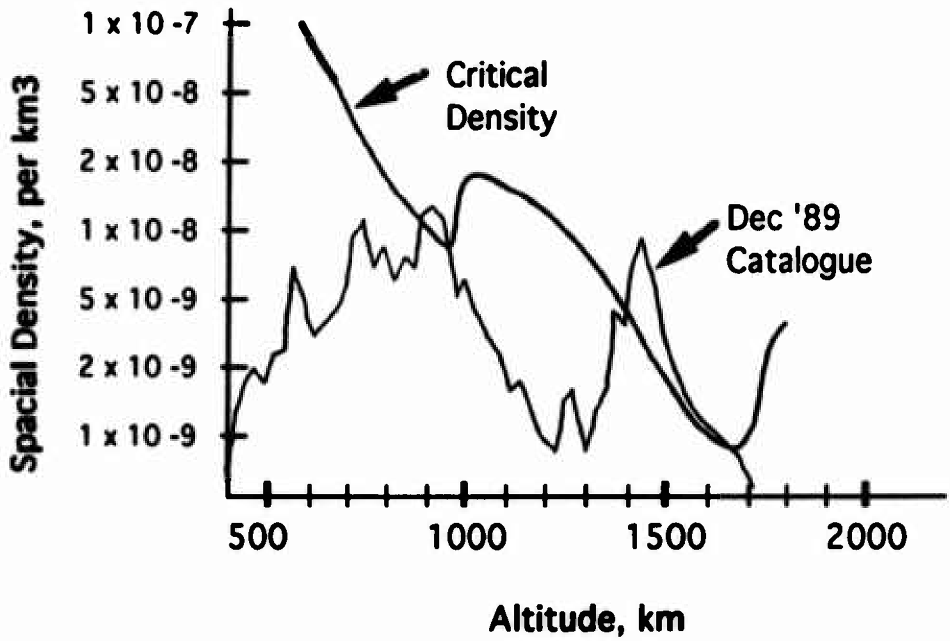

Figure 17. Critical Density Assuming No Uncataloged Objects Larger Than 10 Centimeters and Adjusted for Local Size and Inclination Distributions; Spatial Density of Objects 10 cm or Larger at Various Altitudes[26]

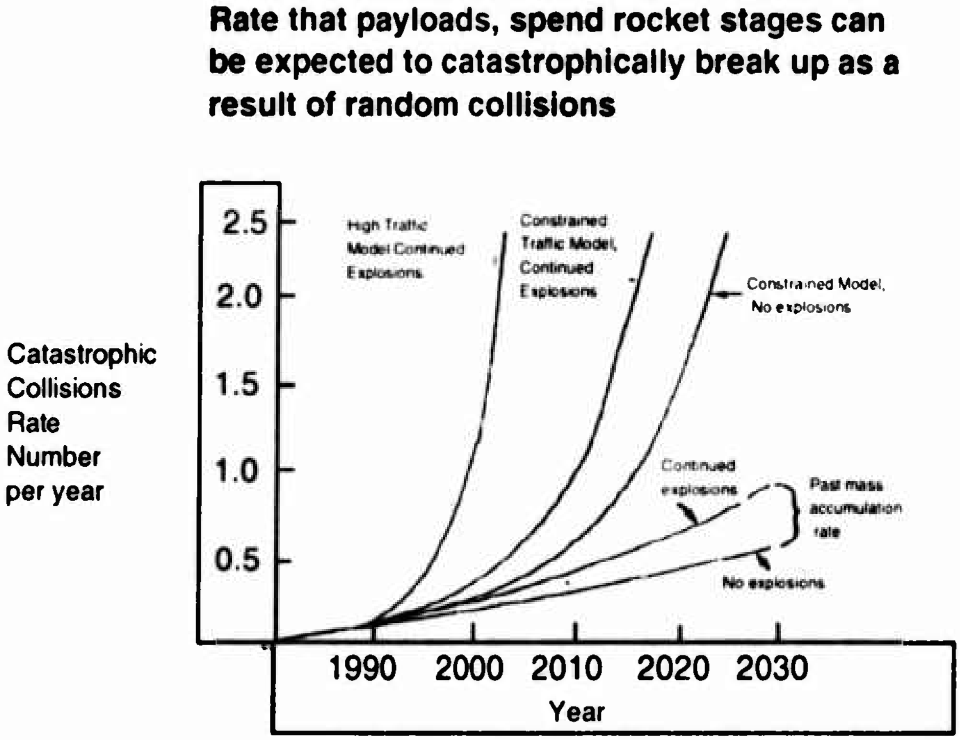

Figure 18. Rate of Catastrophic Breakups Due to Random Collisions at Various Levels of Space Launch Activity as Determined by Kessler[17]

3. SPACE DEBRIS ENVIRONMENT

Determining the amount of debris in orbit is critical in assessing the extent of the present and future space debris problem. There are two main size domains to consider in examining the current space debris environment: larger debris (>10 cm) as represented in the Satellite Catalog and smaller debris (<10 cm) for which a very limited amount of data exists today.

This section looks at the debris environment of low-Earth orbit and the unique case of geosynchronous orbit. It focuses on the available data obtained from the Satellite Catalog. The Satellite Catalog contains information on all satellites and debris that is regularly tracked by United States Space Command using its space surveillance equipment. (Section 5 takes a closer look at space surveillance equipment and examines its limitations for debris observation and analysis.) This section also discusses the available data on smaller, undetectable debris. Most measurements of this type of debris are from *in situ* measurements and have been made possible by using the space Shuttle, which has returned several spacecraft or parts of spacecraft from orbit. Examination of the surfaces of objects that have been retrieved from orbit have provided a useful amount of data on the very small but more numerous debris.

An easy measure of the amount of debris in orbit that gives an indication of the threat it represents is the collisional flux. The collisional flux is defined as the number of impacts per year per square meter for a given size debris or larger. Figure 19 illustrates the bulk of the data available for the range of sizes of debris, and converts the result to collisional flux. Available data comes from a variety of sources. For objects larger than 10 centimeters, the available data is based on the Space Command Satellite Catalog and on specialized debris searches using high powered telescopes. Data on smaller objects was obtained from the number of impacts on objects returned from space, and from a few specialized radar tests. These and other sources of data will be described in detail later in this section. Also included in the debris environment is the natural background meteor flux for the near-Earth environment. Figure 19 shows the limited amount of data on which estimates of the amount of space debris are based. The uncertainties in the available data often is larger than an order of magnitude. No significant source of data exists for objects between 1 and 10 centimeters.

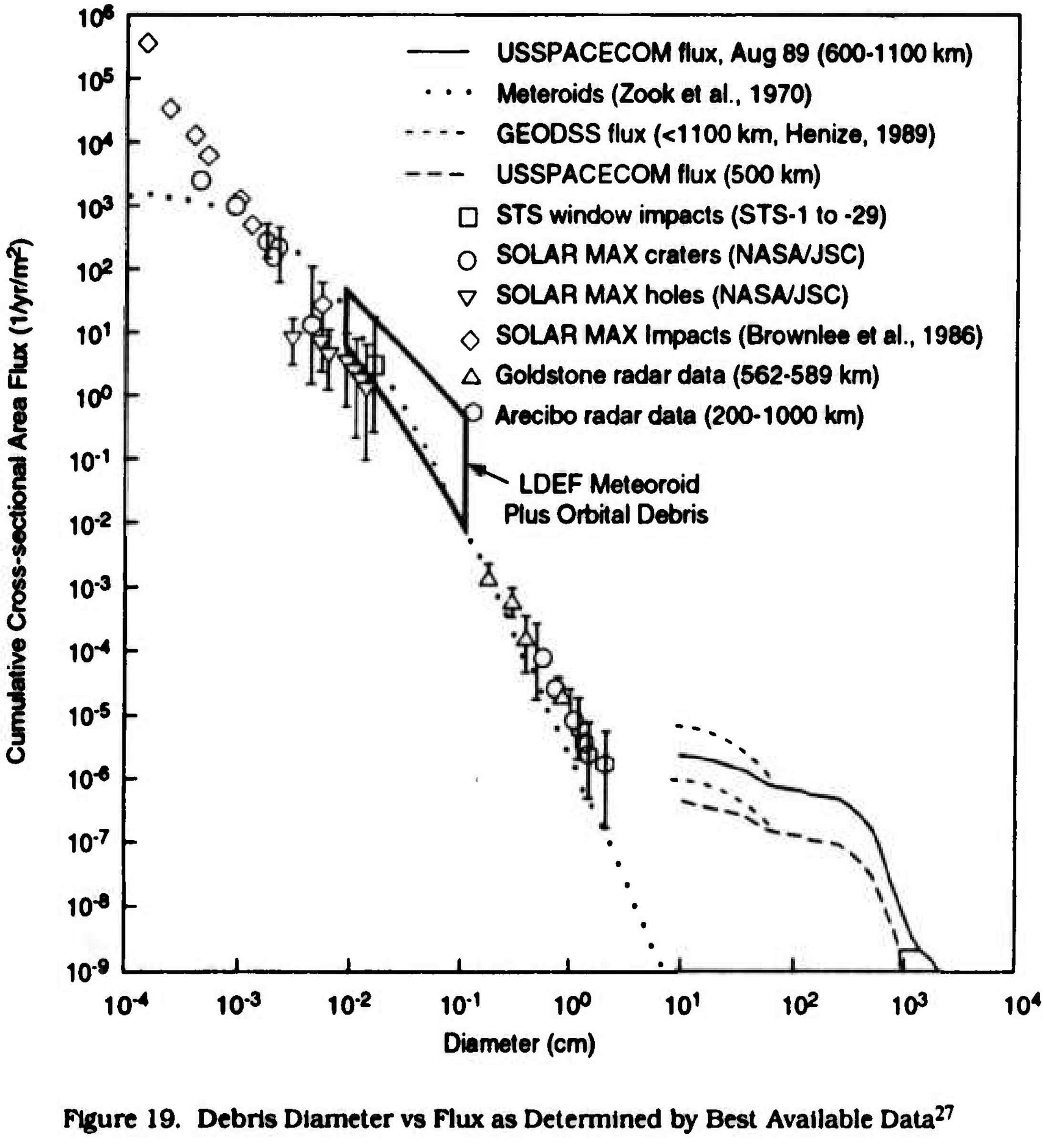

Figure 19. Debris Diameter vs Flux as Determined by Best Available Data[27]

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[27] Debris Chip-LDEF DATA. Orbital Debris Monitor, 1 October 1990, p. 14.

3.1 Low Earth Orbit

The majority of available data on debris in low Earth orbit comes from the Space Command Catalog and from several *in situ* measurements. To characterize the debris in this region we must first examine the Space Command Catalog.

3.1.1 Satellite Catalog Data

The most complete record for the larger debris (>10 cm) is the United States Space Command Satellite Catalog. This catalog lists the satellites and debris regularly detected and tracked by the United States Space Command Space Surveillance System, which consists of an array of radars and other sensors dedicated to observing objects in space. Since the inception of the Satellite Catalog in the early days of the space age, Space Command has cataloged over 20,000 objects in orbit. This is the most comprehensive data base currently available to study the orbital debris environment.

By sorting and analyzing the contents of the Satellite Catalog in different ways, information can be extracted about the amount of debris in orbit and the types of orbits that they occupy. A vast majority of the debris resides in low Earth orbit. Figure 20 shows a breakdown of the number of objects in each type of orbit. Low Earth orbit has been broken into two different categories: LEO1 below 1000 km, and LEO2 between 1000 km and 2000 km average altitude. More than 75 percent of all tracked objects are located below this altitude.

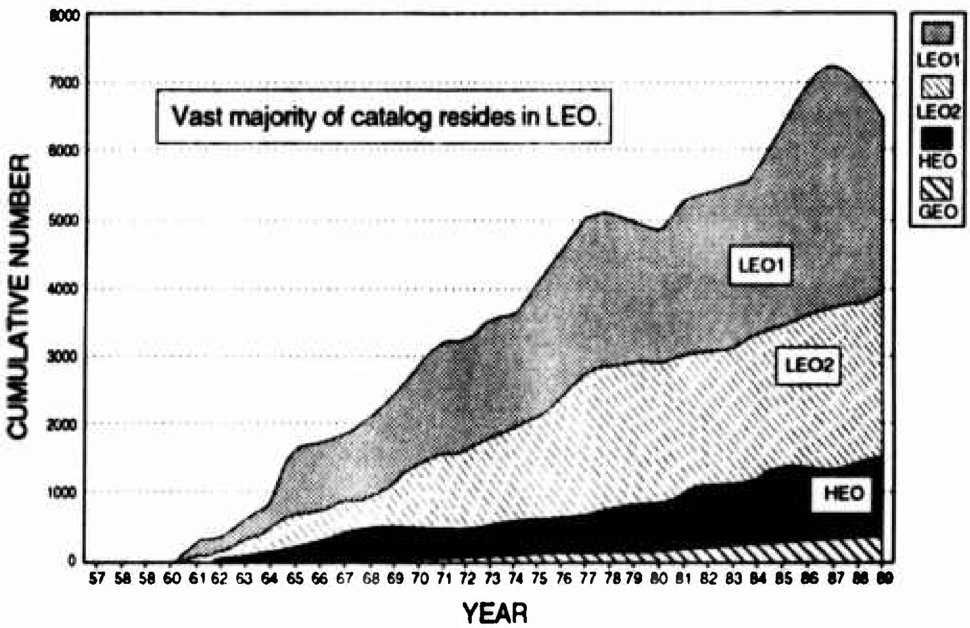

Figure 20. On Orbit Population Growth by Orbital Regime as of 8 December 1989[10]

As discussed in Section 2, fragmentation debris is the major contributor to the number of objects in orbit. Figure 21 details the percentage of each different type of debris by the orbital region it occupies.

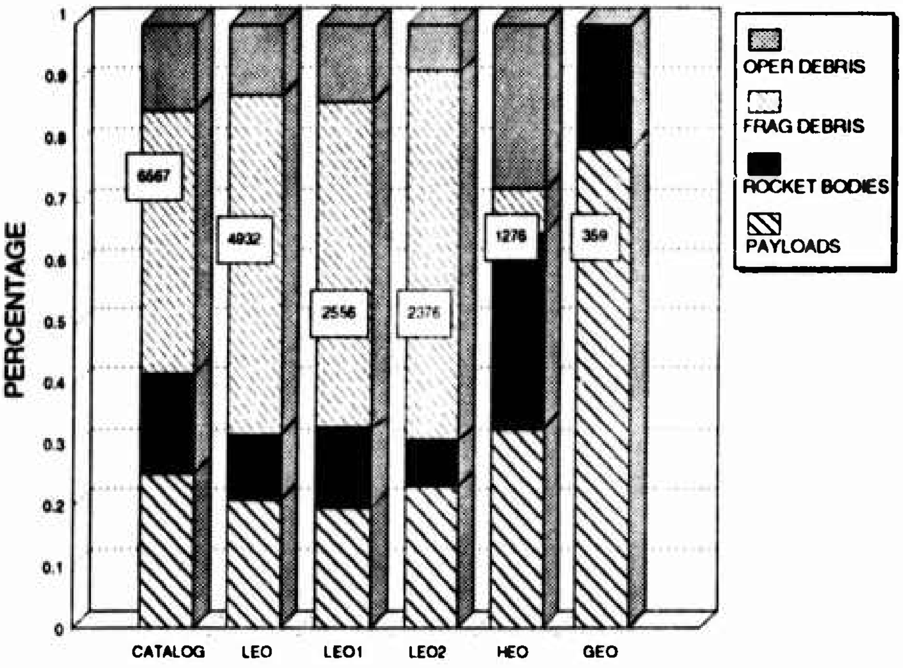

Figure 21. Breakdown of Population in the Various Altitude Region by Type of Debris as of 8 December 1989[10]

The Satellite Catalog has been used to determine the orbits of all objects in space. An argument exists that because a majority of the smaller debris is created by breakups of larger objects, the larger and smaller debris should be in roughly the same orbits. Yet a quick analysis of the objects in the Satellite Catalog, separating them by size, shows that this is not the case. Figures 22 and 23 show the altitude of the large and small objects. While some correlation exists between large spacecraft and debris, it is evident that the smaller objects are spread over a much larger altitude range. Much of this altitude spread is due to the radial velocity imparted during energetic breakups of satellites and rocket bodies. These breakups spread debris over a wide altitude range because of the differing velocities imparted to the different fragments.

A similar situation exists for inclination as for altitude when comparing the orbits of large and small debris. Figures 24 and 25 show the inclination of the large and small objects in the catalog. The narrow lines indicate two things. It first shows that narrow inclination bands are used for numerous satellite systems such as the 63 degree inclination Molniya Orbits, and at the Polar and sun-synchronous orbits at 90 and 100 degrees. Secondly, the transverse velocity imparted on fragments during breakups is small when compared to the orbital velocity. This results in relatively small changes in inclination. Energetic breakups can change the inclination of the fragments by more than 2-3 degrees. Again, there are significant differences between the two distributions, and any space debris model that assumes that the distribution of even smaller non-trackable debris will follow the distribution of the larger trackable debris must be questioned.

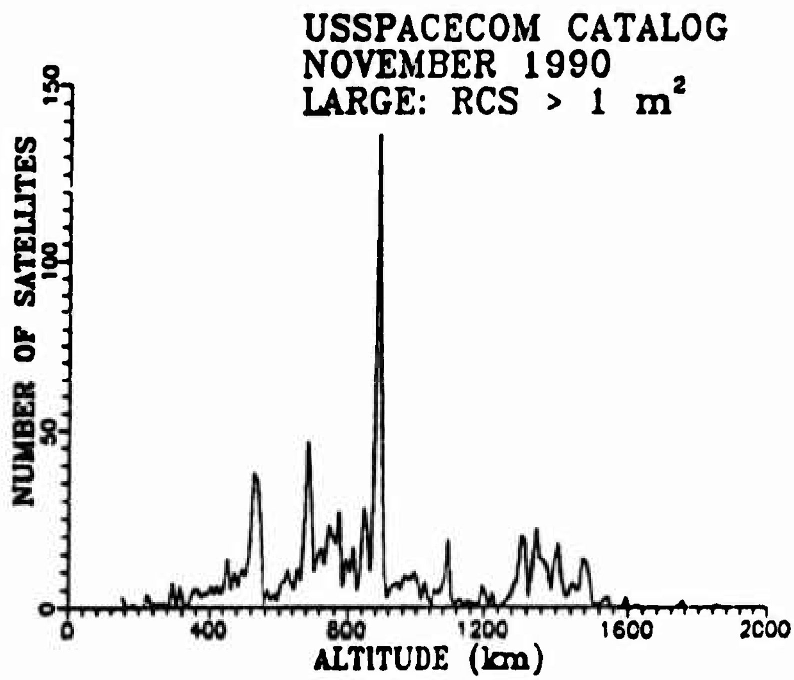

Figure 22. Number of Objects Cataloged Greater Than 1 Square Meter vs Altitude. Size approximated by radar cross section (RCS)

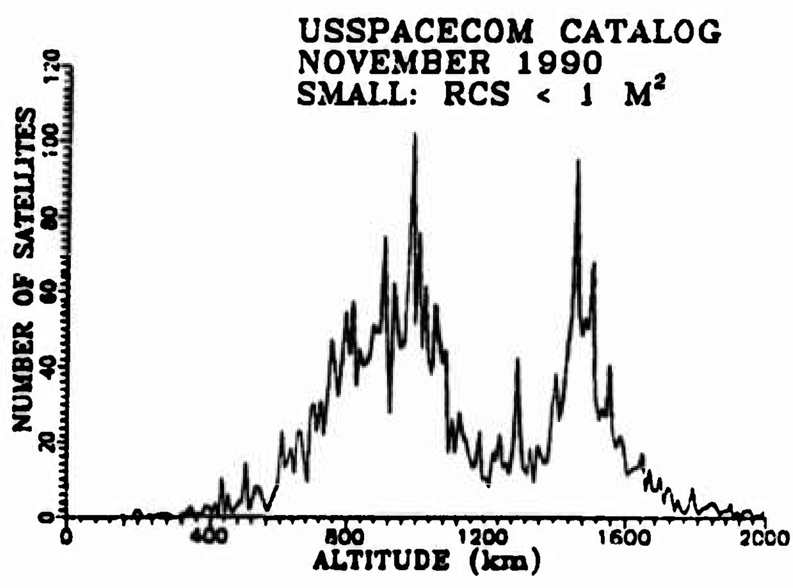

Figure 23. Number of Objects Cataloged Less Than 1 Square Meter vs Altitude. Size approximated by radar cross section (RCS)

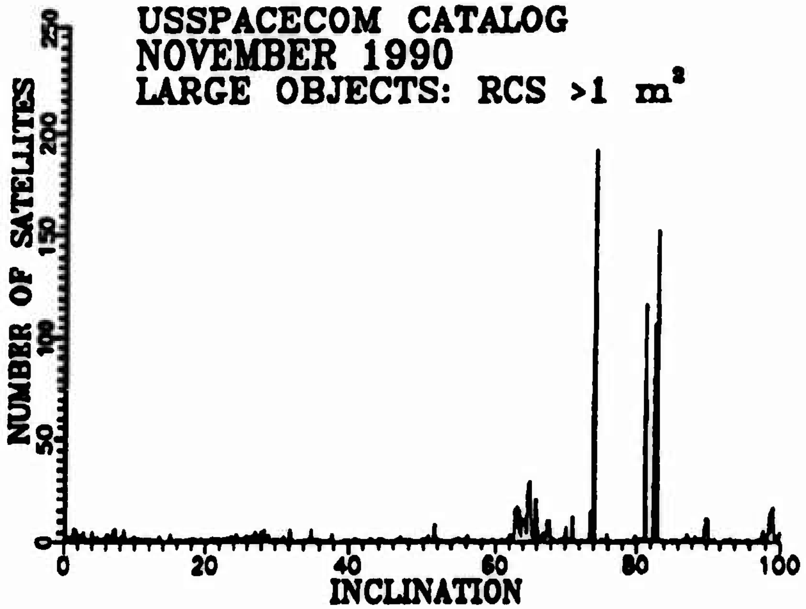

Figure 24. Number of Objects Cataloged Greater Than 1 Square Meter vs Inclination. Size Approximated by Radar Cross Section (RCS)

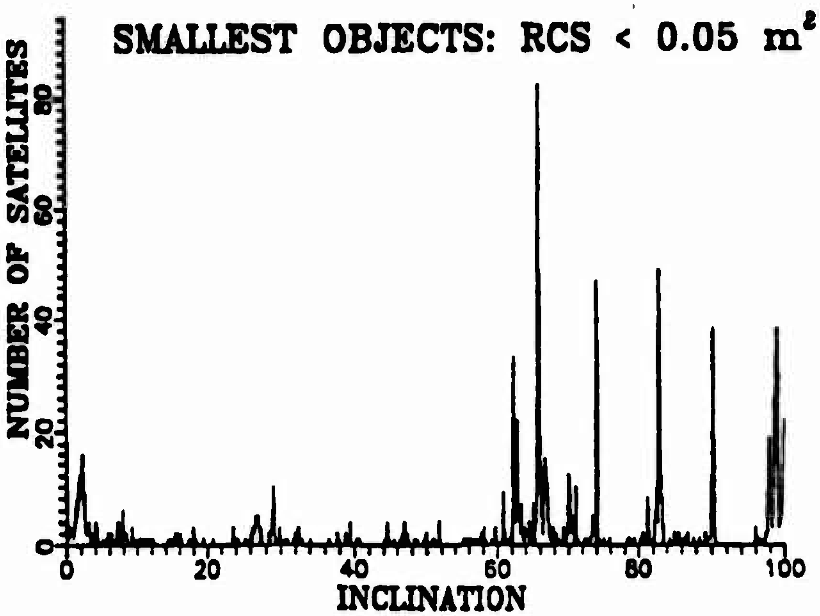

Figure 25. Number of the Smallest Objects Cataloged (Less Than 0.05 Square Meters) vs Inclination. Size approximated by radar cross section (RCS)

3.1.1.1 Initial Test of the Space Command Satellite Catalog

Tests to check the completeness of the Space Command Catalog have indicated thata significant number of objects in the 5 to 25 cm range are not included in the catalog. There have been two well publicized tests that have provided slightly different results. One test was done at the Perimeter Attack Characterization Radar System (PARCS), a large phased array in Concrete, North Dakota. In 1976 and 1978, the radar was set in a fan beam mode in order to detect objects passing through the "fence" of radar energy (a wide fan shaped beam pointing upwards). By correlating objects against those contained in the satellite catalog and maintaining a count of objects detected but not contained in the satellite catalog, these tests indicated that the Space Command Catalog undercounts the orbital population of objects larger than 10 cm by between 7 and 18 percent.[17]

3.1.2 GEODSS DATA

The Ground Based Electro-Optical Deep Space Surveillance System (GEODSS) data contained in Figure 27 is optical data collected by US Space Command for the NASA Johnson Space Flight Center. Johnson Space Flight Center processed 81 hours of optical observations of the space debris environment. These optical observations were made at the Ground Based Electro-Optical Space Surveillance System (GEODSS) at Mt Haleakala, Hawaii, and Diego Garcia in the Indian Ocean. A one-meter telescope was used observing vertically in the morning sky for 1 hour prior to morning nautical twilight.[28] Solar illumination reflected off the debris and was detected by sensitive television cameras attached to the telescope. The results indicated that there were nearly twice as many objects in orbit larger than 10 cm than were contained in the Satellite Catalog.[17]

Results from NASA tests conducted with the Ground Based Electro-Optical Deep Space Surveillance (GEODSS) system with support from Air Force Space Command give another estimate for the completeness of the Satellite Catalog. These tests were conducted at Diego Garcia in the Indian Ocean and at the Maui GEODSS sites. When an object was detected it was cross referenced with the Satellite Catalog in order to correlate it with a known object. Figure 26 shows the reported results from that effort. In Figure 26, "C"'s indicate objects that were in the Satellite Catalog but were not observed; "I"'s indicated objects that were both observed and in the Satellite Catalog; and "N"'s indicates those objects that were observed but were not found in the Satellite Catalog. Although Air Force Space Command has questioned the accuracy of the correlation program used during this analysis, the results show a significant undercounting of the smaller objects in orbit. The larger objects that were observed but not cataloged could be accounted for because of classified objects in orbit that can not be included in the regular catalog.

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[28] Hentze, K. and Stanley, J. (1990) Optical observations of space debris, Article AIAA-90-1340 from the AIAA/NASA/DOD Orbital Debris Conference: Technical Issues & Future Directions, 16-19 April 1990, Baltimore, Maryland.

NASA JOHNSON SPACE CENTER - K. HENIZE / SN3

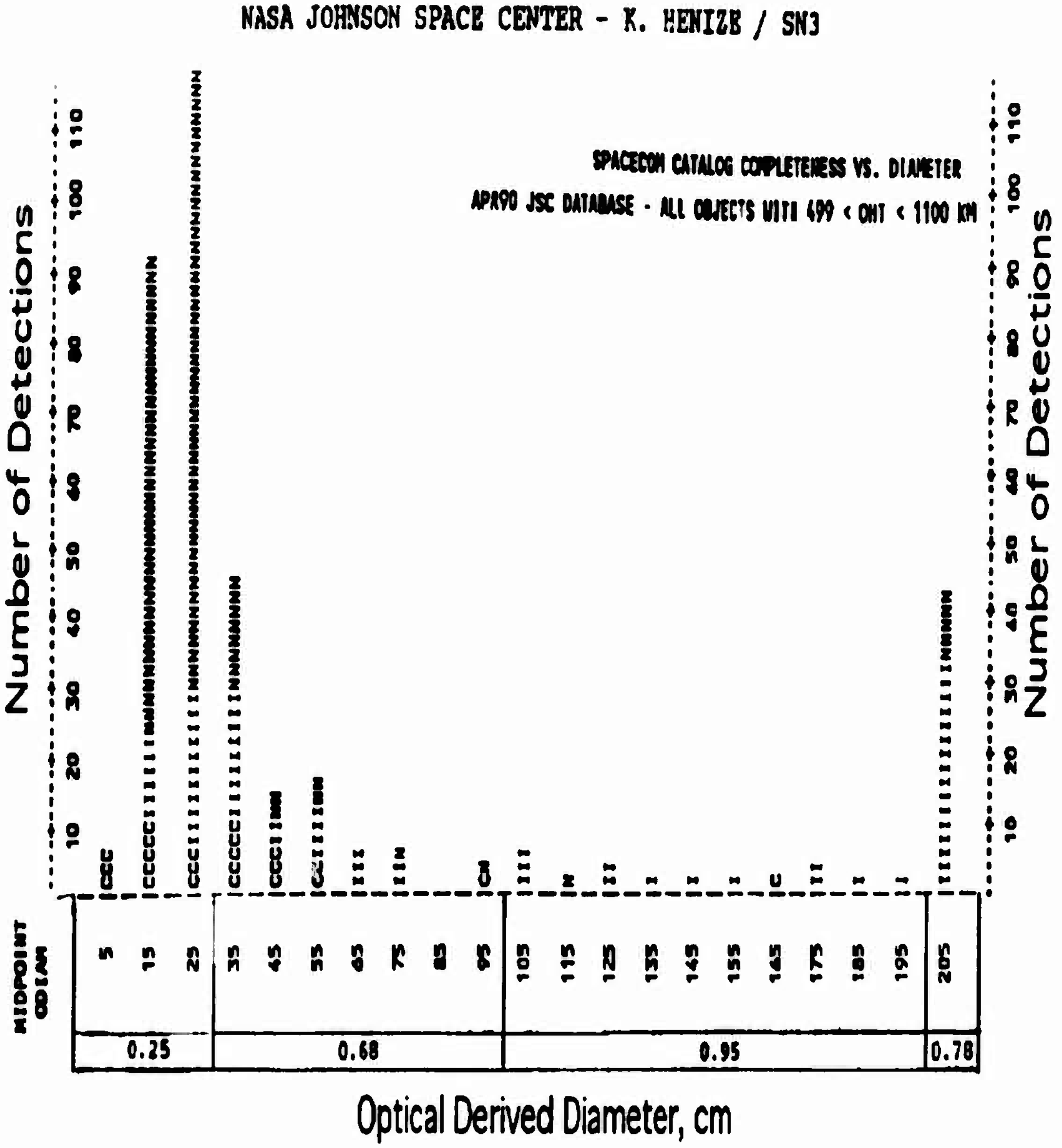

Figure 26 Space Command Catalog Completeness as Determined with the GEODSS Telescopes.[29] (Bottom numbers in the figure are the ratio of cataloged objects to detected objects in the size range indicated)

During the GEODSS tests a total of 622 objects were detected, of which 255 were contained in the Satellite Catalog. These results indicated that the completeness factor (a ratio of the objects contained in the Satellite Catalog to the total objects detected) of the Space Command Catalog is 0.46 over all diameters in the region between 500-1100 kilometers altitude. For objects between 8 and 30 cm, it is reported that the completeness factor is 0.26.[28]

[29] Henize, Karl G. (1991) Optical Debris Observations, briefing at the Optical Debris Measurement Technical Interchange Meeting, Phillips Laboratory, New Mexico, 17 January 1991.

3.1.3 SMALLER DEBRIS IN LOW EARTH ORBIT

The estimate for the small (less than 10 cm) debris population in orbit is based upon a very limited amount of data. The Space Surveillance System cannot detect these objects because of their small radar and optical cross sections. Because of the very limited data base, wide uncertainties exist in the estimates of debris in the range of 1 mm to 10 cm. While several experiments are presently underway to measure this smaller sized debris, the results have not yet been published or been made available for review. The results of the searches that have been published are shown in Figure 19. The limited amount of data continues to leave large uncertainties in the estimates of small debris in orbit.

Data on the very small (less than 0.1 mm), but more numerous objects such as cosmic dust and micro-meteors was obtained from *in situ* measurements based on objects returned from space such as the Space Shuttle, Solar Max heat louvers, and the Long Duration Exposure Facility. These experiments will be discussed in further detail later in this section. These experiments have provided adequate data for estimates of the very small debris population with manageable error limits.

3.1.4 ARECIBO AND GOLDSTONE RADAR EXPERIMENTS

In 1989, two tests were conducted by the Jet Propulsion Laboratory to measure the presence of 0.2 to 0.5 cm and 0.5 to 2 cm sized debris. The Arecibo radar in Puerto Rico collected 14.5 hours of data observing debris between the 0.2 and 0.5 cm range in the 200 to 1000 km altitude region. The Goldstone Radar collected data during 48 hours of observations on debris between 0.5 and 2 cm in the 560 to 590 km altitude region.[30] The results of these radar tests indicated that there was a significantly larger number of particles than was expected due to the natural meteor background, indicating a large man-made debris population in this size region. The results of these experiments presented as a collisional flux are contained in Figure 19 at the beginning of this section. The limited amount of data that was collected contributes significantly to the size of the errors, which are due to the statistics of dealing with a low number of detections.

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[30] Thompson and Goldstein (1990) Arecibo and Goldstone Radar measurements of debris, AIAA Paper 90-1342, from the AIAA/NASA/DOD Orbital Debris Conference: Technical Issues & Future Directions, 16-19 April 1990, Baltimore, Maryland.

3.1.5 METEOR FLUX

The natural meteor flux was estimated by Zook et al in 1970 and is shown in Figure 19.[31] This understanding of the meteor flux is a result of many years of experiments during the early years of the space program. Significant results were obtained by studying the windows from the early Gemini Missions. These experiments were meant to provide hazard information to spacecraft designers. Their results were that the specific density of these particles is between 0.5 and 2 grams per cubic centimeter. This is less dense than expected for manmade space debris. The total influx of meteor material into the atmosphere is approximately 4000 tons per year.[2] The natural debris environment is well understood and remains relatively constant. As shown in Figure 27, the flux for natural particles 1 cm and larger is very low compared to the flux of man-made particles.

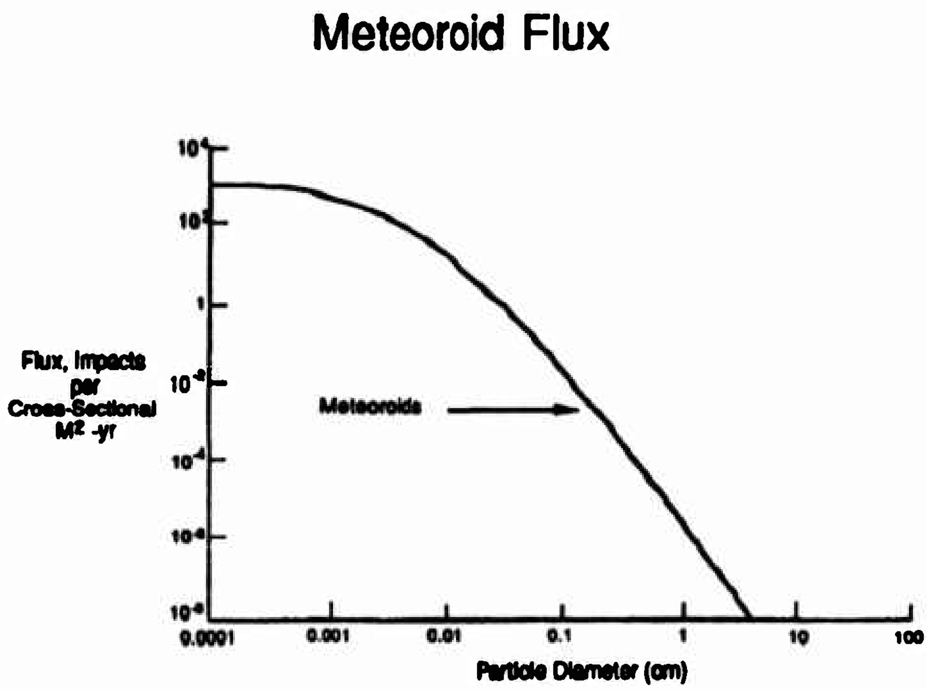

Figure 27. Meteoroid Flux vs Particle Diameter

[31] Zook, H.A., Flaherty, R.E., and Kessler, D.J. (1970) Meteoroid impacts on Gemini windows, *Planetary Space Science*, **18** (No 7): 953-964.

3.1.6 *IN SITU* MEASUREMENTS

Measurements of smaller debris rely mainly on the analysis of objects returned from space. The three major contributors for such information came from the Space Shuttle windows, the parts returned during the repair of the Solar Max satellite, and the retrieval of the Long Duration Exposure Facility.

3.1.6.1 Shuttle Measurements

The shuttle windows are inspected after each flight to ensure an adequate level of safety for the next flight. On one occasion the window was replaced after being impacted by a paint chip. Other shuttle based experiments included placing one square meter of aluminium foil in the cargo bay and polished surfaces on the shuttle boom.[12]

3.1.6.2 Solar Max

Solar Max was launched in February 1980 into a low inclination low-Earth orbit. In April 1984, astronauts from the Space Shuttle repaired the satellite after it had malfunctioned. This allowed the return of roughly 3 square meters of exposed surfaces that had spent over 4 years in orbit. This provided a considerable amount of data on the small space debris environment. The returned surfaces consist of the thermal control louvers and some insulating blankets of the satellite that were removed from the satellite during repairs. These surfaces were exposed for 4.15 years before being returned to Earth. Sources of the craters are determined by analysis of projectile residue left around and inside the crater by electron microscope and Energy Dispersive X-Ray (EDX) Compositional Analysis.[32] Analyses indicate that on the louvers, impacts of meteors and man-made debris in the range of 10^{-9} to 10^{-7} grams were roughly equal in numbers. Smaller particles were dominated by paint chips.[32] Of the larger craters, 47 were of meteoric origin, 7 were from manmade debris, and 6 were of unknown sources.[32] A possibility exists that the unknown sources were aluminum, because then there would be no detectable trace of extra debris left in the crater since the aluminum of the debris would be masked by the aluminum in the louvers. If the impacts of unknown origin were caused by aluminum particles, which are expected to make up a large part of the small debris population, then the debris population smaller than 10^{-5} grams is twice that reported by Zook and McKay.

[32] Zook, Herbert A., Mckay, David S., and Bernhard, Ronald P. (1990) Results from returned spacecraft surfaces, Article AIAA-90-1349 from the AIAA/NASA/DOD Orbital Debris Conference: Technical Issues & Future Directions, 16-19 April 1990, Baltimore, Maryland.

3.1.6.3 Long Duration Exposure Facility

The Long Duration Exposure Facility (LDEF), shown in Figure 28, was designed to measure the effects of atomic oxygen, space radiation and space debris on a variety of materials. It was launched into a 478 km altitude, 28 degree inclination orbit by the Space Shuttle in April 1984 and was recovered in January 1990. Its expected one year in orbit turned into 5.8 years in orbit due to the Space Shuttle Challenger explosion and the grounding of the shuttle fleet.

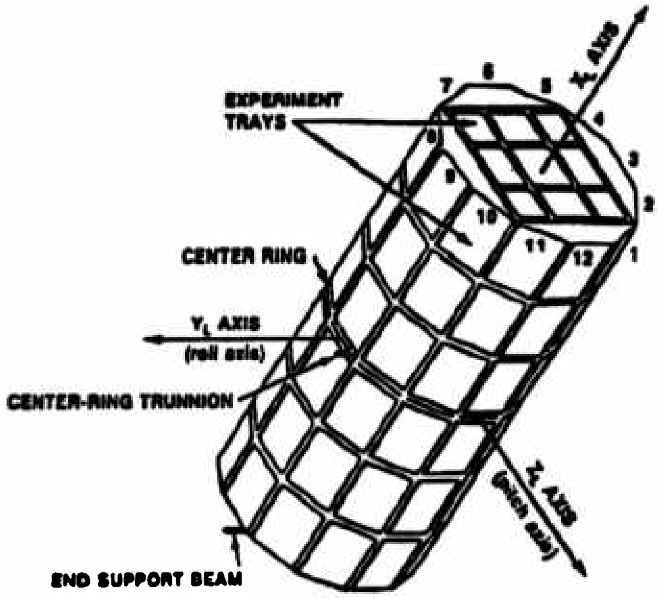

Figure 28. The Long Duration Exposure Facility Configuration

Initial analysis of the LDEF surfaces indicate that it had suffered over 34,000 impacts. Of these craters, over 5,000 were found to to be in the 0.5 to 5 mm range, with the largest being 5.25 mm in diameter.[22] The analysis also indicated that the leading edge of LDEF received approximately 20 times the number of impacts as the trailing edge.[22] This is due to the velocity of the spacecraft in orbit causing the spacecraft to "sweep up" debris as it traveled. Figure 29 shows the direction of impact of debris on the LDEF spacecraft. Figure 30 shows the relative number of debris impacts per panel.

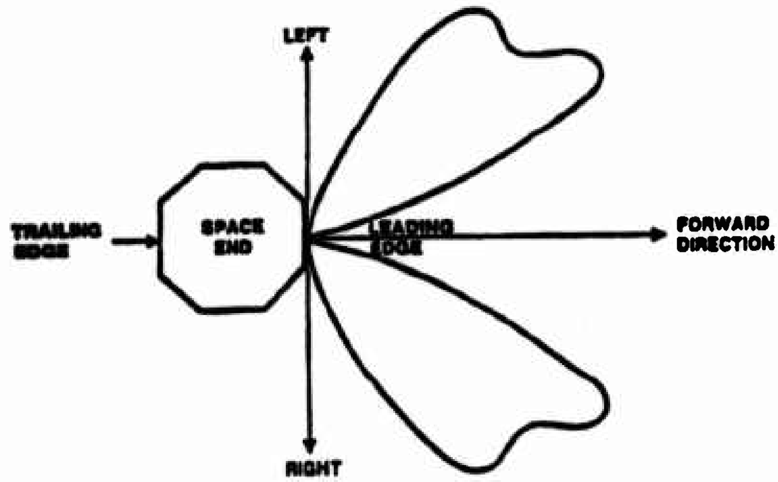

Figure 29. Direction of Orbital Debris Impact as Viewed From Above the Spacecraft[22]

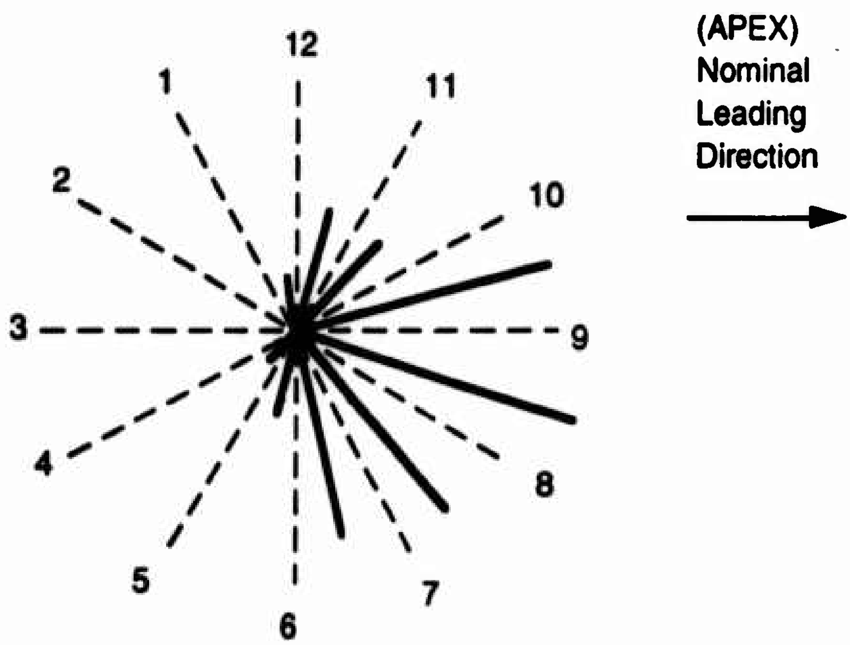

Figure 30. Relative Number of Impacts Greater than 0.5 mm by Panel Number (433 impacts). (The length of the dark lines are proportional to the number of impacts per panel)[22]

While the preliminary results available from LDEF have been published, it will take several more years to learn as much as possible from this important test.

3.1.7 LACK OF DATA ON OBJECTS 1 TO 10 CM

While these experiments have provided adequate data on small debris and the Space Command Catalog is adequate for large debris, there exists a large gap in the available data on space debris in the range between 1 mm and 10 cm. Radars and other devices used for the Space Surveillance Network are restricted in the size of objects they can detect, thus limiting the value of their databases of small debris measurements. The small radar and optical cross sections of this range of debris make them very difficult to detect. What limited data does exist on debris between 1 cm and 10 cm is small compared to the data required to provide a full and complete characterization of the near-Earth environment. In this range, the probability of collisions is not high enough to provide estimates to characterize the population through *in situ* measurements such as LDEF or Solar Max. Significantly larger spacecraft, such as the Space Station would have to spend many years in orbit to accumulate adequate information.

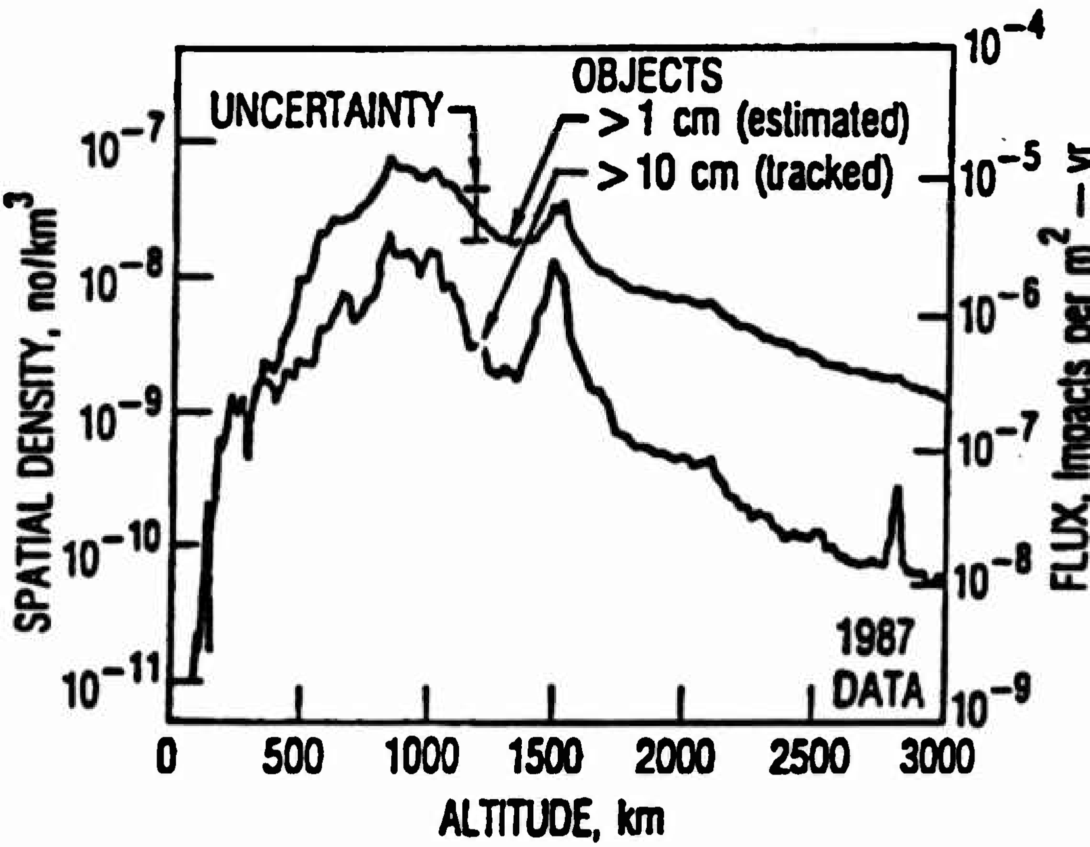

Figure 31. Orbital Debris Density vs. Altitude[22]

3.2 Geosynchronous Orbit

Because of the unique property of the geosynchronous orbit, it is the orbit of choice for communications satellites, early warning satellites and a host of other satellites. Most of the satellites are found in a narrow altitude and inclination band to keep them apparently stationary over a single point on the Earth. As of March 1991 there were 350 objects contained in the Satellite Catalog at geosynchronous orbit. These included 284 spacecraft and 66 rocket bodies. Of the 284 payloads in geosynchronous orbit, approximately 110 to 130 are still operating, and 150 are nonfunctional or abandoned.[22] Figure 32 shows how these objects are distributed around the Earth.

The main users of the geosynchronous ring are the developed nations. The United States has 90 satellites in geostationary orbit and the Soviet Union has 74. Other countries and the number of satellites each has in geosynchronous orbit are shown in Table 9.

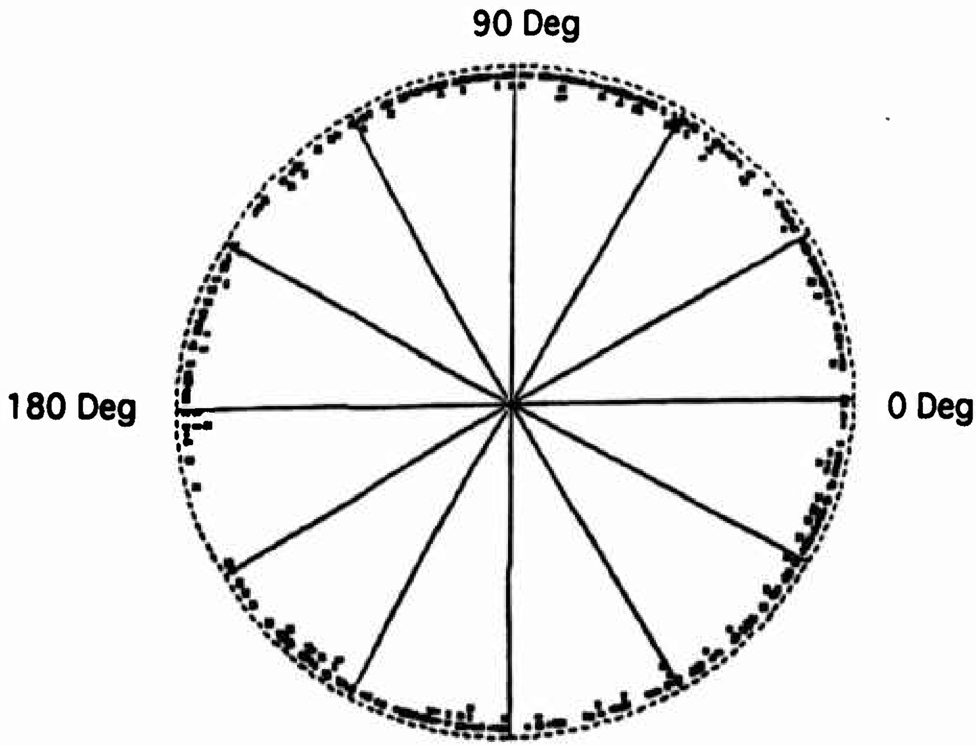

Figure 32. GEO Population Longitude Distribution.[22] Zero degrees is located over Greenwich, England

Table 9. Objects in Geosynchronous Orbit by Country

OWNER	Spacecraft	Rocket Bodies
United States	90	11
Soviet Union	74	66
Great Britain	9	--
Italy	1	--
Canada	10	--
France	4	--
Australia	3	--
Japan	18	--
Germany	4	--
NATO	6	--
China	5	--
India	5	--
European Space Agency	12	--
France/Germany	2	--
Indonesia	5	--
ITSO	29	--
Brazil	2	--
Saudi Arabia	2	--
Mexico	2	--
Luxemburg	1	--
Total	284	66

What worries the space debris community about geostationary orbit is not the present number of objects in orbit, but instead the rate of growth of these objects. With the requirement for more communication and other types of satellites, the population in geosynchronous orbit is expected to continue to grow. Figure 33 shows the growth rate of objects with a radar cross section larger than one square meter in geosynchronous orbit. The growth rate of 25 per year is twice that of the low-Earth orbit on a percentage basis.

The number of satellites in geosynchronous orbit is limited by the amount of separation between satellites required to provide interference-free operation. Earlier satellites required a few degrees separation to keep radio signals and command signals from interfering with other satellites or ground stations. With the development of higher frequency communication satellites, individual satellites can be positioned at the same longitude. This is known as co-location. An example of co-location occurred when in 1977 the World Administrative Radio Conference (which allocates the geostationary positions) allocated the 19 degree west slot plus or minus 0.1 degrees to several different satellites. The TDF-1, the Olympus and the TVSAT-2 are in the area and will be joined by the TDF-2 satellite. These four satellites in the same longitude position in geosynchronous orbit execute uncoordinated station-keeping maneuvers, and the expected time between close encounters of 50 m or less is 0.6 years.[33]

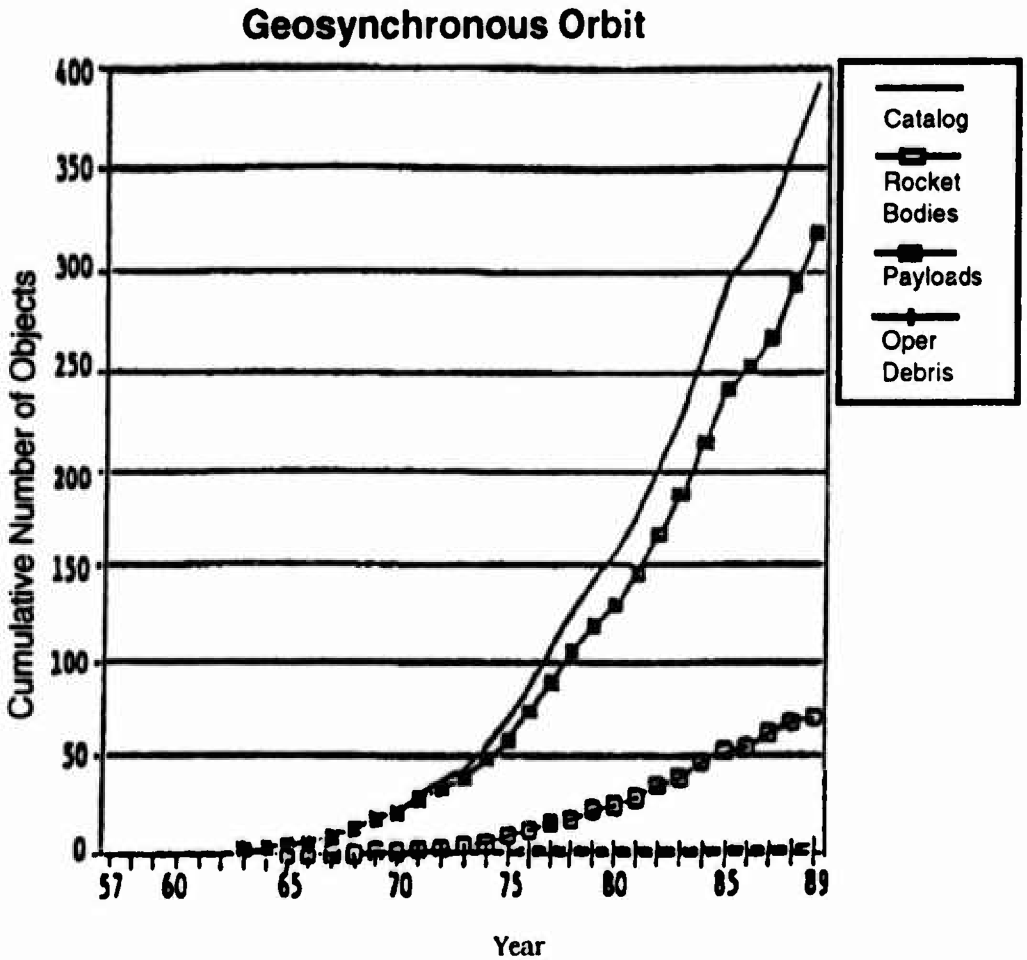

Figure 33. Geosynchronous Catalog Population Growth History[22]

Collisions between objects in geostationary orbit are at a relatively low velocity when compared to that of low-Earth orbit debris. Most objects are travelling at approximately the same velocity and inclination. Controlled satellites are kept close to zero inclination. North-south station keeping maneuvers are required to keep the satellites in the proper inclination orbits because of the effects of the Sun and the Moon. Drift rates for uncontrolled objects are 0.9 degree per year. This effect necessitates a 40-42 meter per second change in velocity per year to maintain

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[33] Flury, W. (1990) Collision probability and spacecraft disposition in geostationary orbit, European Space Operations Center, ESA, Darmstadt F.G.R. XXVIII COSPAR 1990, Paper No MB.2.2.3.

north-south station-keeping. Thus the amount of available fuel is typically the limiting factor in the lifetime of a geostationary satellite.

The velocity between an object in perfect station-keeping (0 degrees inclination) and one that has been allowed to drift for one year (0.9 degrees inclination) as the satellite crosses the equatorial plane is nearly 120 km/hr. Collisions between two satellites at this velocity, while not causing the amount of debris that a hypervelocity impact would cause, would still cause a significant amount of debris.

The major concern of the space debris community is that a collision or a fragmentation event in geosynchronous orbit will significantly increase the amount of space debris at that altitude. The result of a single breakup could cause other on-orbit collisions with other satellites. Since there are no natural removal mechanisms from geosynchronous orbit, this can result in an unstable debris population that is self-perpetuating (the Kessler effect). Also since there are no removal mechanisms, any debris created will remain a threat to all future geosynchronous systems. Since geosynchronous orbit is a non-renewable global resource, measures to minimize this threat are of greatest importance.

3.2.1 COLLISION PROBABILITY IN GEOSYNCHRONOUS ORBIT

Because so many objects are concentrated in a narrow band near the geostationary altitude, the collision probability in that region is orders of magnitude higher than a few hundred kilometers higher or lower. The threat of a single satellite colliding with another object is small at the present time. The collision probability is given in Figure 34. The inclination is included in the determination of collision probabilities because at higher inclinations, the relative velocities between the satellite and the objects in geosynchronous orbit are greater.

When all the satellites in geosynchronous orbit are considered, the collisional risk is significantly higher. The probability of a collision between one thousand 1 meter square objects in geosynchronous orbit orbit over 20 years is 0.021. If that number were increased to 10,000 objects the probability of collision in 20 years is 0.16. The probability of collision at the stable points (75 degrees East and 105 degrees West longitude) increases by a factor of 2.[33]

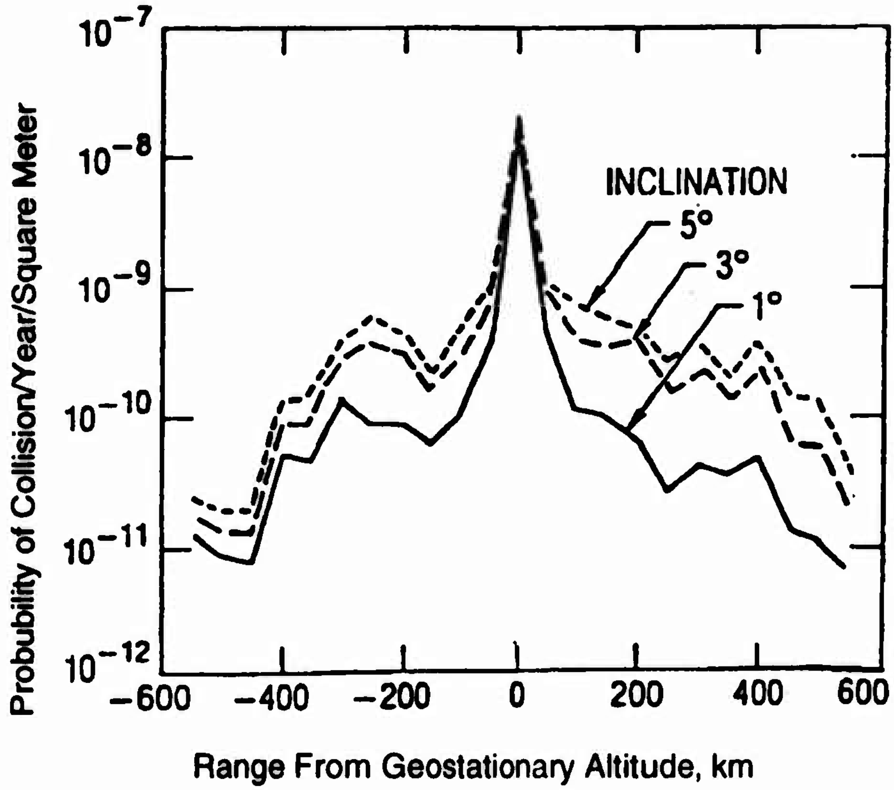

Figure 34. Collision Probability for Geosynchronous Orbit[22]

3.3 Risk to Space Systems

A collision damage study done by Dr. Phan Dao of the Geophysics Directorate of the Phillips Laboratory outlines the Air Force's concerns associated with space debris.[34] The Air Force is interested in five different orbital regimes, ranging from geosynchronous orbits to low altitude polar orbits.

Regime A: High Altitude/Geosynchronous
0 deg < inclination < 67 deg
Altitude = 35,000 km

Regime B: Mid Altitude/Mid Inclination
55 deg < inclination < 70 deg
10,360 km < Altitude < 20,350 km

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[34] Dao, Phan (1990) Collision Hazard Study: Potential impact of orbital debris on low earth orbit satellites, briefing given at Phillips Laboratory, November, 1990.

Regime C: Low Altitude East
28 deg < inclination < 32 deg
Altitude = 1,850 km

Regime D: Low Altitude/Mid Inclination
60 deg < inclination < 80 deg
Altitude = 1,850 km

Regime E: Low Altitude Polar
90 deg < inclination < 100 deg
Altitude = 7,400 km

The collisional risks associated with each regime are different due to the varying density of the debris environment and the characteristics of the orbits.

The geosynchronous regime is a particularly valuable orbit because of its unique earth-rotation matching period and was discussed earlier. This orbital band is a global resource used by communications, early warning and weather monitoring satellites. It is a natural, non-renewable resource that requires protection. Orbital slots are assigned by the United Nations, and the United Nations determines who can use the different positions in geosynchronous orbit while maintaining the required separation dictated by command, control, and communications requirements. The present collision hazard rate at geosynchronous orbit is low, approximately 10^{-8} impacts/(sq meter year).[22] However, some problems do exist. As discussed earlier, co-located satellites may have up to one encounter per year with near misses as close as 50 meters.[35] Thus, collision hazard in this orbit will continue to grow as more objects are placed in geosynchronous orbit. Debris resulting from collisions between objects in orbit, although at low relative velocities, would result in a significant increase in the number of objects in this orbit. This could have a profound effect on the collision hazard rate, especially since at this orbit there is no natural cleansing mechanism.

The mid-Earth orbit (MEO) is a high value orbit for military systems such as navigation systems. Currently very little is known about the debris population in this orbit. Because of the relatively low debris population, collisions with space debris are not a major concern in these orbits at this time. In addition, most navigation satellites systems such as GPS, TRANSIT and GLONASS that occupy these orbits consist of constellations so that the failure of a single satellite will not cause a significant decrease in capability.

The low-Earth orbits (LEO) are of primary concern with respect to space debris. The LEO polar and LEO mid inclination orbits contain several critical surveillance satellite systems for the Department of Defense and other government agencies.[36] These are high priority, very expensive satellites. Low-Earth orbit also contains the vast majority of the objects in space. Yet, the actual

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35 Bird, A.G. (1990) Special considerations for GEO-ESA, Article AIAA-90-1361 from the AIAA/NASA/DOD Orbital Debris Conference: Technical Issues & Future Directions, 16-19 April 1990, Baltimore, Maryland.

36 Bamford, James (1983) *The Puzzle Palace*, New York, Penguin Books Ltd.

risks are not exactly known because detailed analysis of the collisional hazard rate is hampered by the lack of data on the amount of debris in low-Earth orbit. This causes large uncertainties in the resulting calculated collisional probabilities.

Looking at the characteristics of the planned Department of Defense satellites and the results from a NASA space debris model, developed to aid the design of the Space Station[37], it is possible to obtain a measure of the potential problems caused by space debris. Using a best case/worst case scenario, it is possible to get a sense of the range of expected outcomes. The space debris flux per unit area is found by using the NASA TM 100-471 Engineering Model. The number of predicted collisions will be the product of the space debris flux, the area of the satellite and the number of years in orbit. The best possible case will be characterized by using the minimum flux predicted by NASA and a fixed launch rate of 120 satellites per year. It will also use only the main body of the satellite when determining the effective area of the satellite. The worst case scenario will be calculated by using the maximum flux predicted by NASA and a launch rate increase of 5 percent per year. In this case the main body, solar panels, booms and antennas will all be considered when determining the effective area. These parameters are summarized in the Table 10 below.

Table 10. Parameters for Best Case/Worst Case Scenarios

Parameter	Best Case	Worst Case
1) Flux (impacts/sq meter/year)	Min NASA Flux	Max NASA Flux
2) Surface Area	Main Body Only	Main Body +Solar Panels, Antennas and Booms.
3) Launch Rate	Linear (120/yr)	Increasing by 5% per year

A sample of the results obtained by running the NASA model is shown in Figure 35. The dashed center line represents the predicted flux at a given debris size or larger. The solid lines indicate the range of uncertainty associated with the model. Any object to the right of the vertical line labeled assumed lethal size is assumed to be lethal. This model is most accurate in the low

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37 Kessler, D.J., Reynolds, R.C., and Anz-Meador, P.D. (1988) *Orbital Debris Environment for Spacecraft Designed to Operate in Low Earth Orbit*, NASA TM 100-471.

inclination (28.5 degrees), low-Earth orbit (>700 km) region, the expected orbit of the Space Station. The further away the satellite of interest is from this orbit, the higher the errors become.

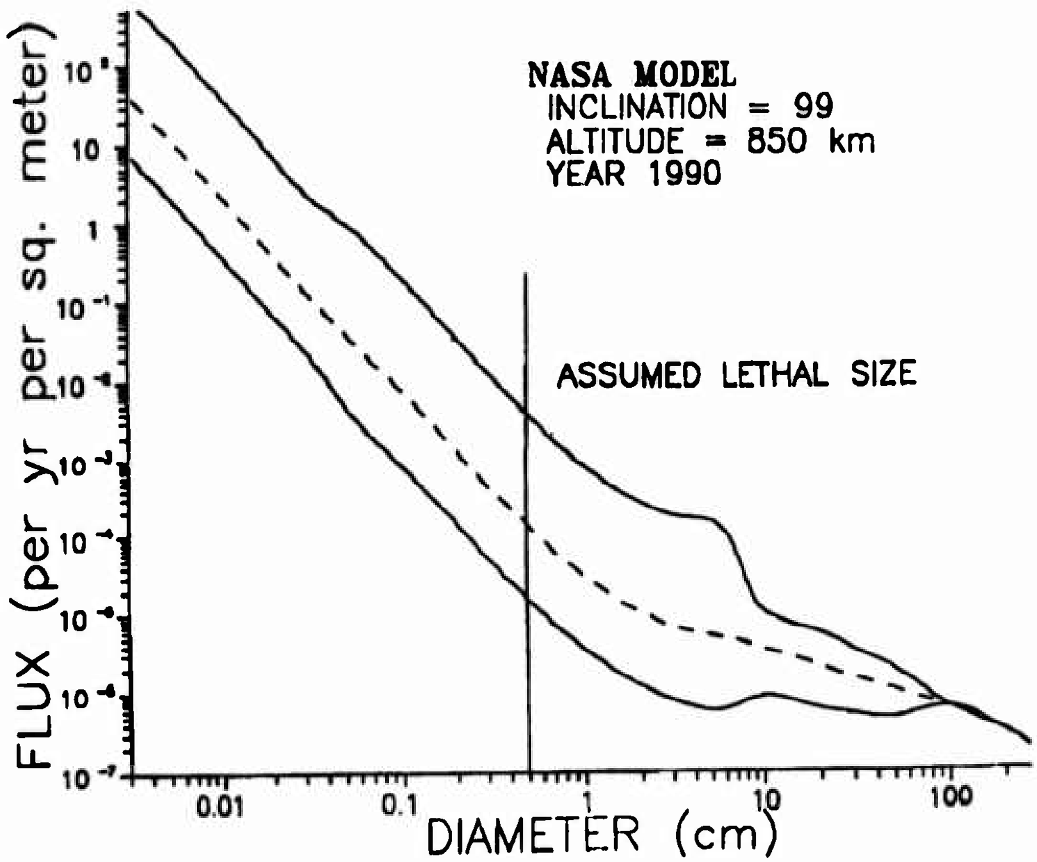

Figure 35. Sample Results of NASA Model Flux for Inclination of 99 Degrees at 850 Km Altitude in 1990

The flux was set to match a range of planned Department of Defense satellite systems. Many of the Department of Defense planned satellites are classified, but several systems are widely known. The Space Based Radar and the Navy's LightSat program are good examples of the types of satellites being considered. The best case/worst case analysis, the number of collisions per constellation with a lethal sized piece of debris (assumed to be 0.5 cm) are obtained for 12 future satellite systems and are presented in Table 11. Figures 36 and 37 show the range of collisions per constellation as a function of altitude and inclination.

Table 11. Satellite Hazard Analysis for 12 Future Department of Defense Satellite Systems

Satellite	1	2	3	4	5	6	7	8	9	10	11	12
Start/End Dates	1990 2010	1990 2010	1990 2010	1990 2010	2000 2020	2000 2020	2000 2020	1990 2010	1990 2010	1990 2010	1990 2010	1990 2010
Number of Satellites	2	1	6	4	6-12	6-12	6-12	2	2	2	2	2
Altitude	850	850	1150	1150	650	650	1150	400	400	1500	1500	1500
Inclination	99	99	63	63	70	70	70	90	90	63	63	63
Best * Case (Minimum)	0.02	0.04	.004	0.3	0.03	0.03	0.2	0.2	0.2	0.2	0.1	0.1
Worst * Case (Maximum)	4	1	1	66	34	25	150	1.6	2.1	53	21	28

* Number of Collisions per Constellation Over the Life of the Constellation

Figure 36 shows the best and worst case estimates of the number of collisions per constellation over the life time of the constellation at the various altitudes of the satellite systems. Figure 37 plots the same information as a function of inclination.

From these figures, it is clear that there are orders of magnitude of uncertainties in thehazard assessment for any Department of Defense satellite system. In the best case scenario, the damage risk is relatively insignificant compared to the risks associated with launch and on-orbit failures. In the worst case scenario the risk due to orbital debris is very significant. The true answer most likely falls between these two extremes. The driving uncertainty in the hazard analysis is the uncertainty of the model itself. The primary uncertainty in the model is the lack of available data to develop adequate models.

The number of objects in orbit continues to increase. The Space Command Satellite Catalog provides the most complete information for large objects in orbit; however, radar and optical tests of the completeness of the Space Command Satellite Catalog indicate that a significant number of objects are not included. Correlation between the orbits of the larger and smaller objects contained in the Satellite Catalog indicate significant differences, making use of the Satellite Catalog to predict the population of small objects questionable. Debris measurements smaller than 10 cm are limited to a few radar, optical and in situ measurements, with very little data in the critical region between 1 and 10 centimeters The result is that large uncertainties exist in what is known about the debris environment. These large uncertainties in the debris environment translate directly into uncertainties in the risk to space systems.

The conclusion is that an aggressive debris measurement effort is required to minimize the uncertainties in the threat of debris to Department of Defense and other space systems.

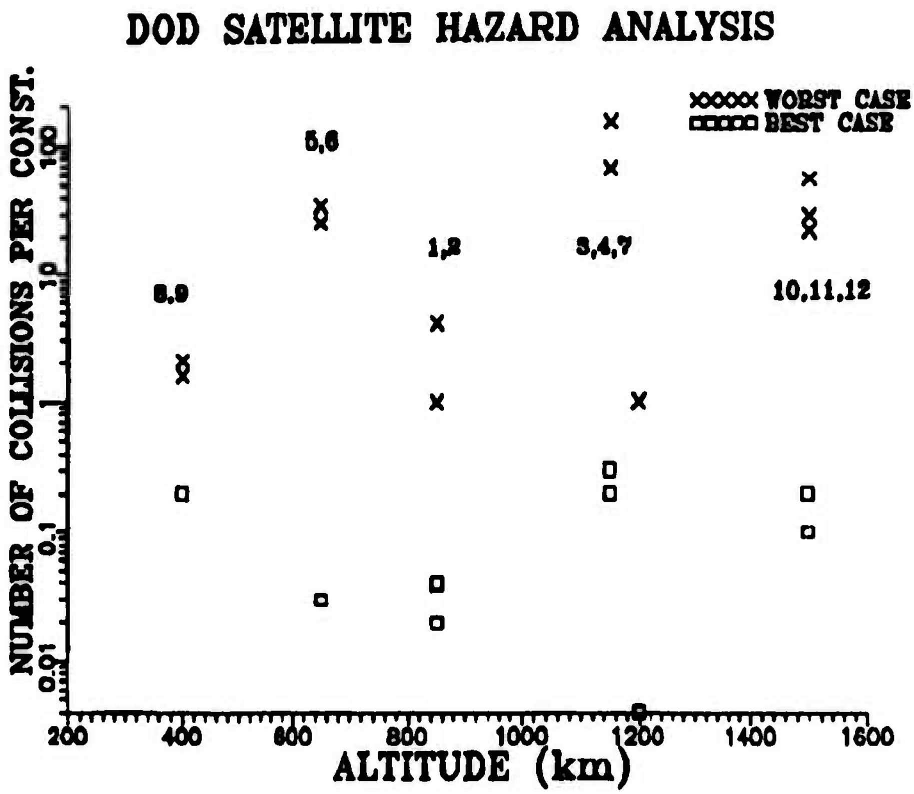

Figure 36. Department of Defense Satellite Hazard Analysis for Altitude and Inclination Dependence

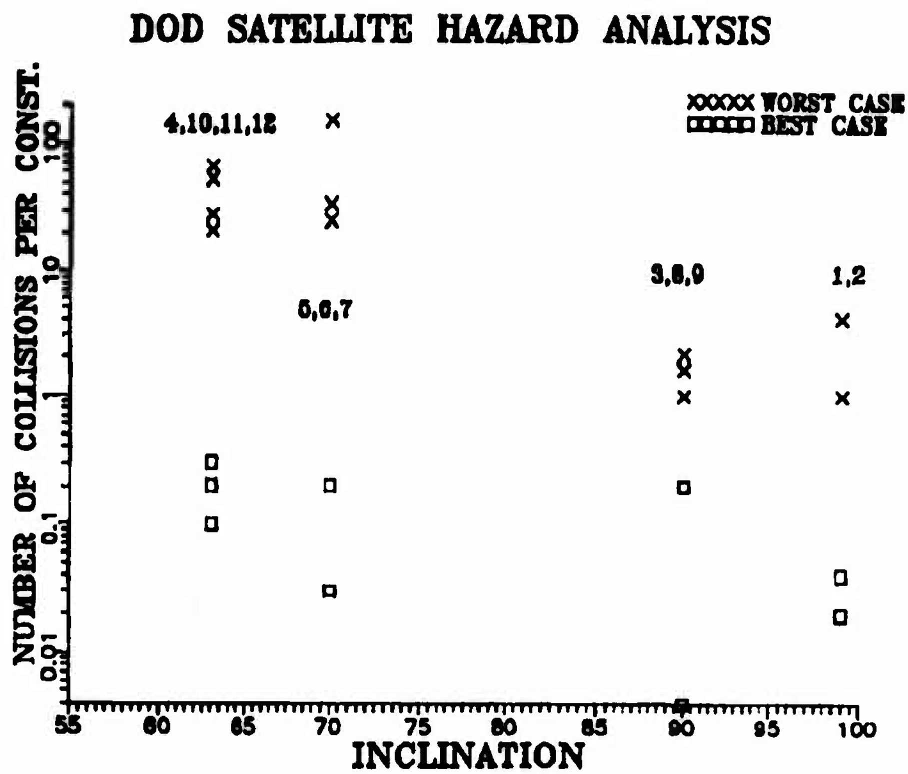

Figure 37. Department of Defense Satellite Hazard Analysis for Altitude and Inclination Dependence

4. COLLISION DAMAGE

This section analyzes the dangers of, and the possible damage caused by, space debris. First it examines the characteristics of an orbital collision between two objects. Then it looks at the different damage scenarios and how they could affect different systems. The results from hypervelocity impact tests undertaken for anti-satellite weapon development tests are used to estimate the results of high velocity collisions. Finally, the section examines the results and possibilities of collisions with space debris of several present and planned space systems.

4.1 Velocity of Collisions

Space debris is particularly dangerous to operational systems in space due to their high relative velocities, and therefore the large kinetic energies involved in collisions with them. This makes even small objects a hazard for manned or critical space systems. The velocity of a collision is the difference between the orbital velocities, as shown below in Eq. (3).

$$\overrightarrow{V_{Col}}=\overrightarrow{V_s}-\overrightarrow{V_D} \tag{3}$$

Where:

V_{Col} = Velocity of collision
V_s = Velocity of the satellite
V_D = Velocity of debris

Because orbital velocities are very large, it does not take a large angle of intercept to cause hypervelocity collisions. High velocity collisions are possible between objects with the same inclination because of the differences in right ascension. Figure 38 shows two geometries for a sample collision in orbit.

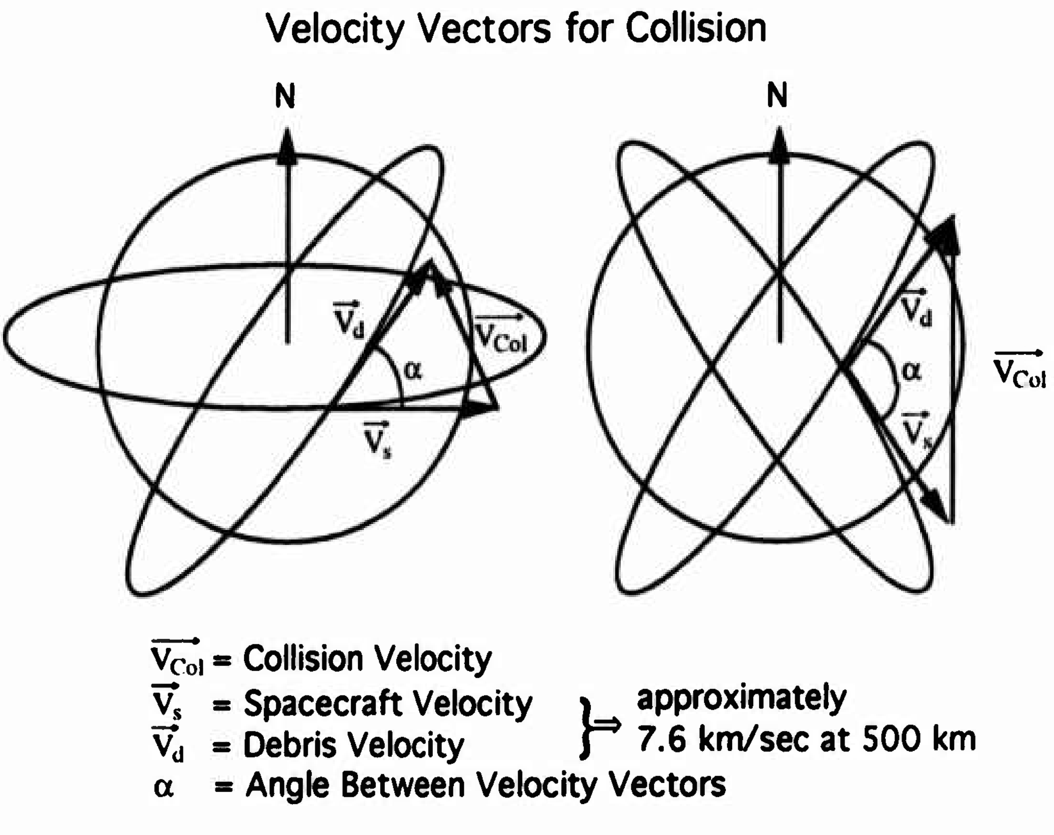

Figure 38. Geometry for Orbital Collisions

Figure 39 shows the orbital velocities for circular orbits at various altitudes. The orbital velocity for a 500 km orbit is approximately 7.6 kilometers per second.

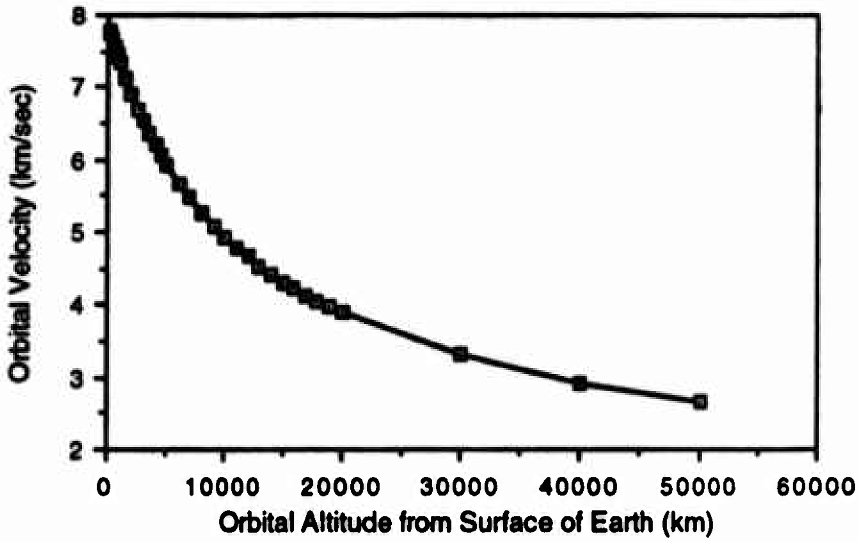

Figure 39. Orbital Velocities for Circular Orbits at Various Altitudes

The expected collisional velocity between objects is modelled by NASA as part of their Evolve Debris Code. In this model, NASA determines the percentage of impacts that will occur in a given velocity range. Figure 40 shows the normalized velocity probability distribution of a collision for objects in a 500 km and 28.5 degree inclination orbit as found by the NASA model.[38] It shows that the majority of orbital collisions in this orbit will occur at very high velocities, between 8 and 14 kilometers per second.

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[38] Mog, Robert A. (1991) Spacecraft protective structures design optimization, *Journal of Spacecraft and Rockets*, January-February 1991, pp. 109 - 117.

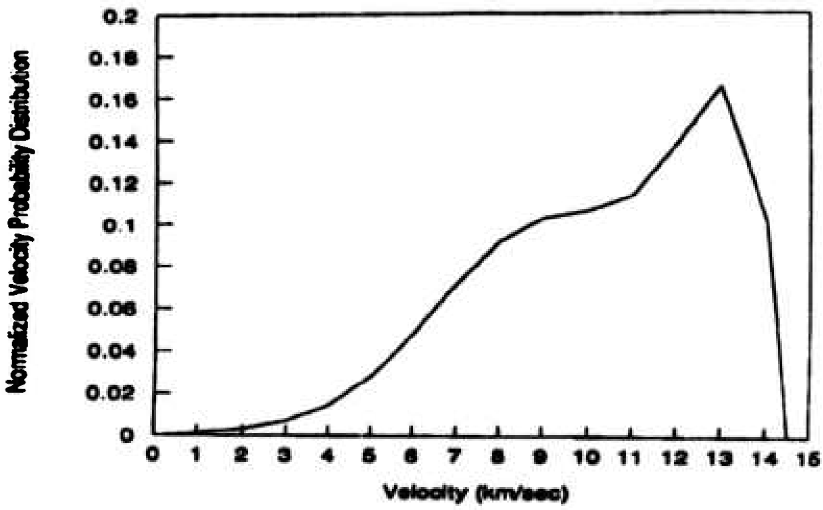

Figure 40. Normalized Collisional Probability at a Given Velocity for a 28.5 Degree Inclined Orbit[38]

The kinetic energies involved in these hypervelocity collisions are large because of the high velocities associated with orbital collisions. For instance, an object weighing one tenth of a milligram that travels at 1 km/sec has 0.1 joule of kinetic energy, approximately the same as a speck of sand in a sand storm. The same object traveling at 10 km/sec has the force of a baseball pitched from a pitcher. A 10 milligram object at 1 km/sec has the same energy as the baseball, while the same object at 10 km/sec will have the force of a 30.06 rifle round. A 100 gram object traveling at 10 km/sec has the same energy as a ton of TNT. The kinetic energy of pieces of space debris at various speeds is plotted against the weight of the debris in Figure 41.

This comparison is not entirely accurate. A ton of TNT would spread its explosive force in a spherically symmetric manner, spreading its energy in all directions. The energy of space debris is concentrated only at the area of impact. While it is not that difficult to design a system that can withstand explosions in close proximity, it would be nearly impossible to design a space system that could both withstand a collision with a large piece of debris and still meet a reasonable launch weight.

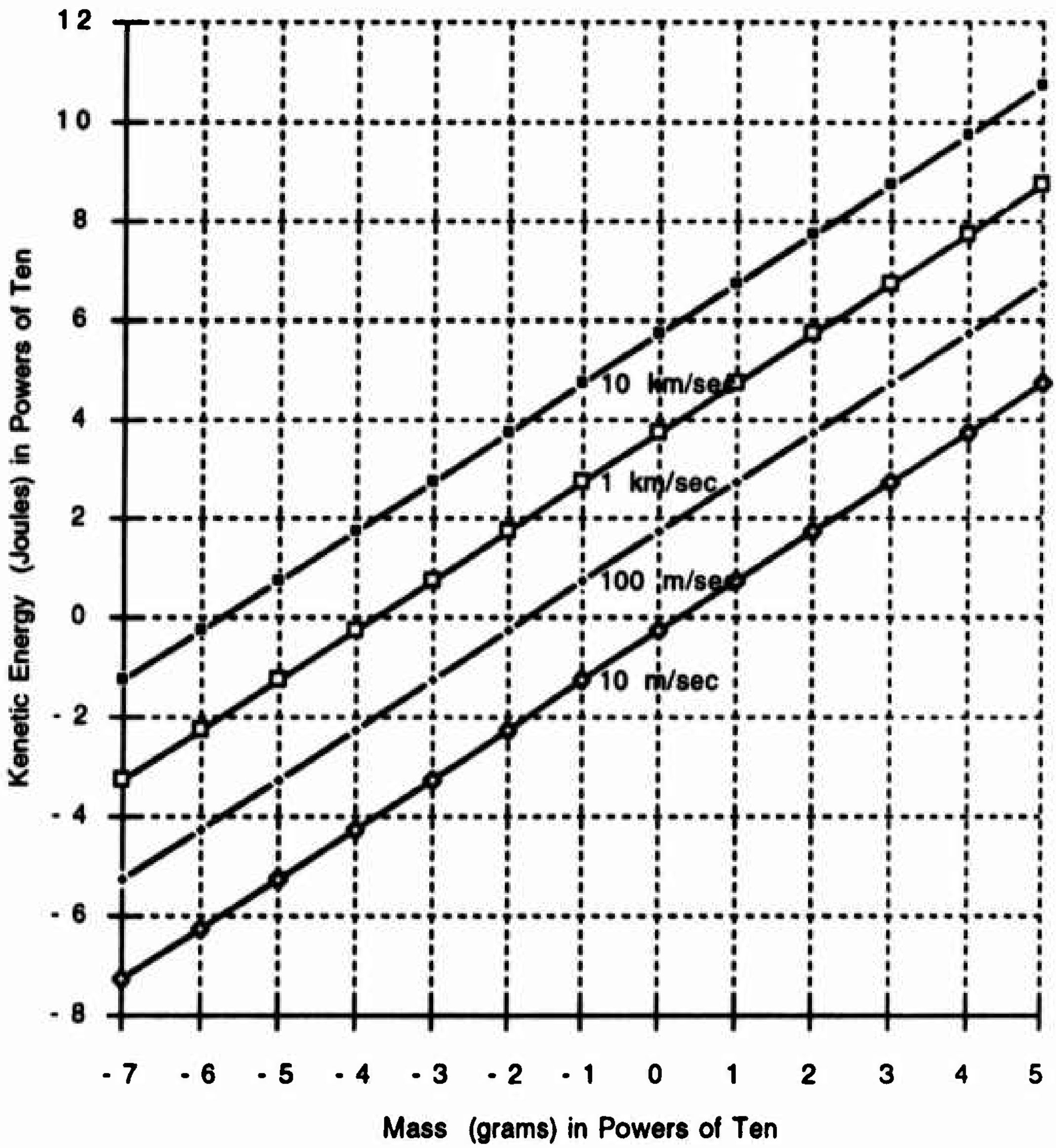

Figure 41. Log-Log Plot of Kinetic Energy of Space Debris at Various Velocities

4.2 Damage Mechanisms

A number of different mechanisms can cause damage to space systems in a hypervelocity collision. The damage to the spacecraft depends on the velocity, the size, and the material of the impacting debris. Most damage is in the form of craters caused by the impacting object and its fragments. Even without penetrating a bulkhead or protective cover a collision can cause damage by other mechanisms. Particles can spall off the inside of impacted surfaces. These particles in turn can cause additional damage. Other damage mechanisms include shock waves caused by an impact and carried though the spacecraft, or a possible pressure pulse caused by the vapor created in the collision. Figure 42 shows an example of a collision where the debris penetrates the spacecraft skin. Figure 43 shows some of the important parameters and effects of a hypervelocity impact in which a particle penetrates the spacecraft skin.

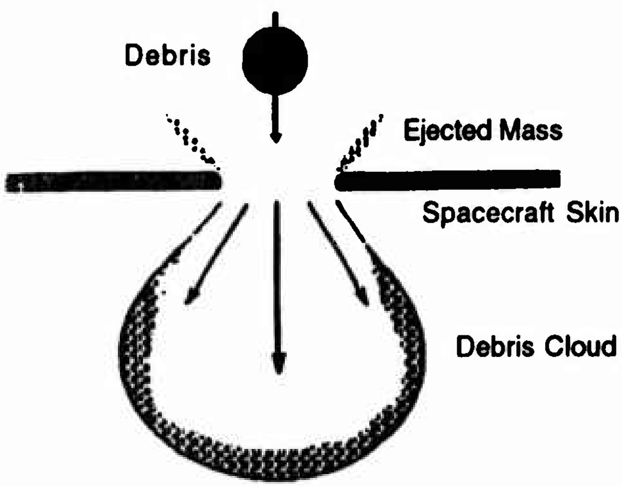

Figure 42. Initial Collision of Debris with a Spacecraft

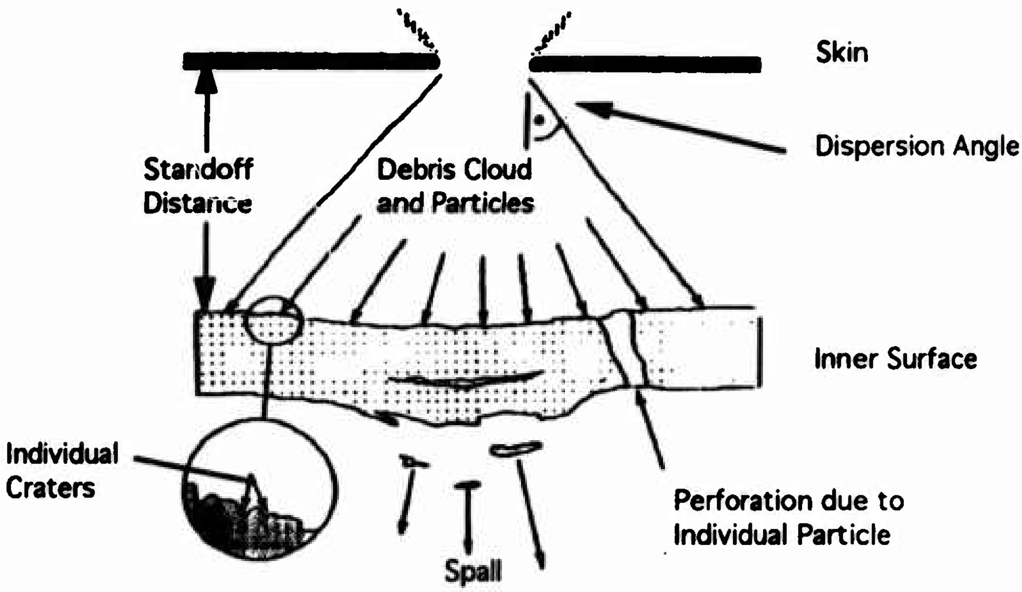

Figure 43. Secondary Collisions Within a Satellite

All hypervelocity collisions are not the same. The characteristics of damage depend largely upon the collisional velocity and the nature of the debris. At relatively low velocities (0-3 km/sec), the piece of debris is deformed and stays relatively intact as it penetrates the satellite. This allows for deep penetration at a single point and is similar to damage done by a bullet.

At higher velocities (3-7 km/sec), the debris will fragment into a large number of pieces so surfaces inside the skin of the satellite will be sprayed with a large number of high velocity debris. These smaller fragments will spread with a dispersion angle that distributes subsequent impacts over a larger area.

At even higher velocities, (7-14 km/sec) the debris fragments and vaporizes during the initial collision. The resulting cloud of particles and gasses spreads prior to colliding with subsequent surfaces where they deposit the rest of their energy in an impulse-like manner. The impulsive force can cause ripping or tearing of subsequent surfaces. During the initial and subsequent collisions, part of the impacted surface will also be broken off or vaporized, adding to the total amount of projectiles.

The density and boiling point of the debris, in addition to its velocity, determine the results of its impact with a surface. Higher density objects will have greater penetration depths because of their greater mass per unit surface area. Debris with higher boiling or vaporization temperatures require more time after collision to reach these temperatures. This allows the object to penetrate further before breaking up into smaller fragments. Figure 44 shows a representative curve for the relative penetrative ability of a 1-centimeter aluminum projectile over a wide range of velocities. Note that the highest penetrative ability is between 2 and 4 km/sec because in this region the resulting fragments are relatively large as compared to higher velocities where the debris fragments into smaller particles or vaporize.

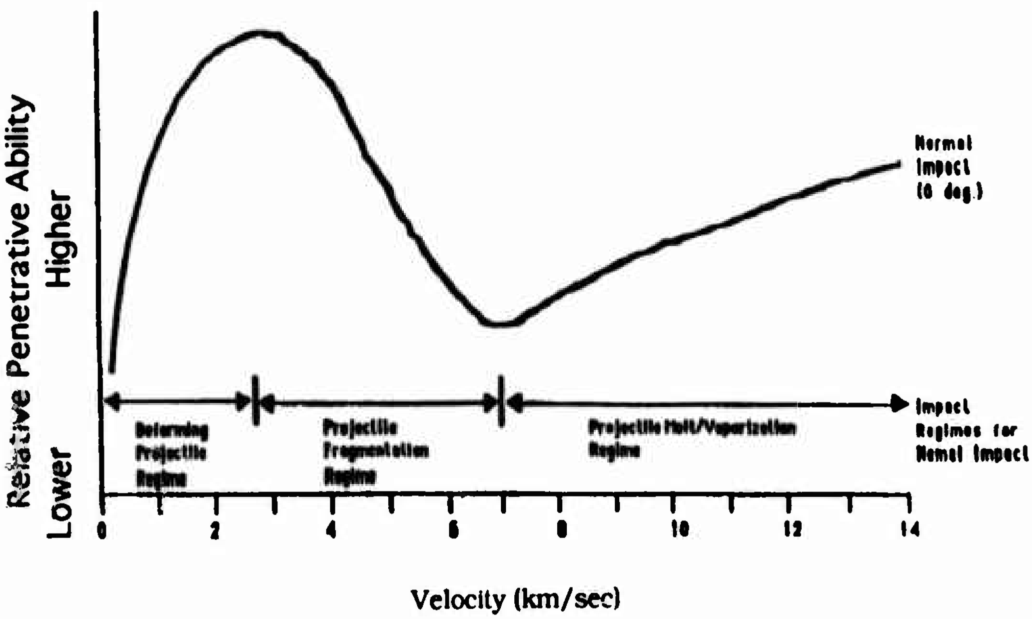

Figure 44. Relative Penetrative Ability at Different Velocities for a 1 Centimeter Diameter Aluminum Debris[39]

4.2.1 PARTICLE IMPACT

At best most satellite skins will not stop collisions with debris larger than a few millimeters. The outer skin of a satellite is usually a thin piece of sheet metal. Typically, it is not meant to act as a shield against space debris. Damage to the skin itself by a small piece of debris would be insignificant. However, if the debris can puncture the skin, fragments can continue into the spacecraft and cause significant damage inside it. This type of damage is detailed in the hypervelocity impact tests discussed later in this section.

After an initial collision, the spray of fragments continues on into the spacecraft. Figure 45 describes many of the damage classifications of particle damage after an initial collision with a

39 Adapted from chart "Ballistic Limit Curves" from briefing "Meteoroid/Debris Shielding" presented by Eric Christiansen at the Phillips Laboratory Orbital Debris Technical Interchange meeting 2-3 April 1991.

light skin or shield of a spacecraft. This information was presented in a NASA briefing at the Phillips Laboratory Orbital Debris Technical Interchange meeting.[40]

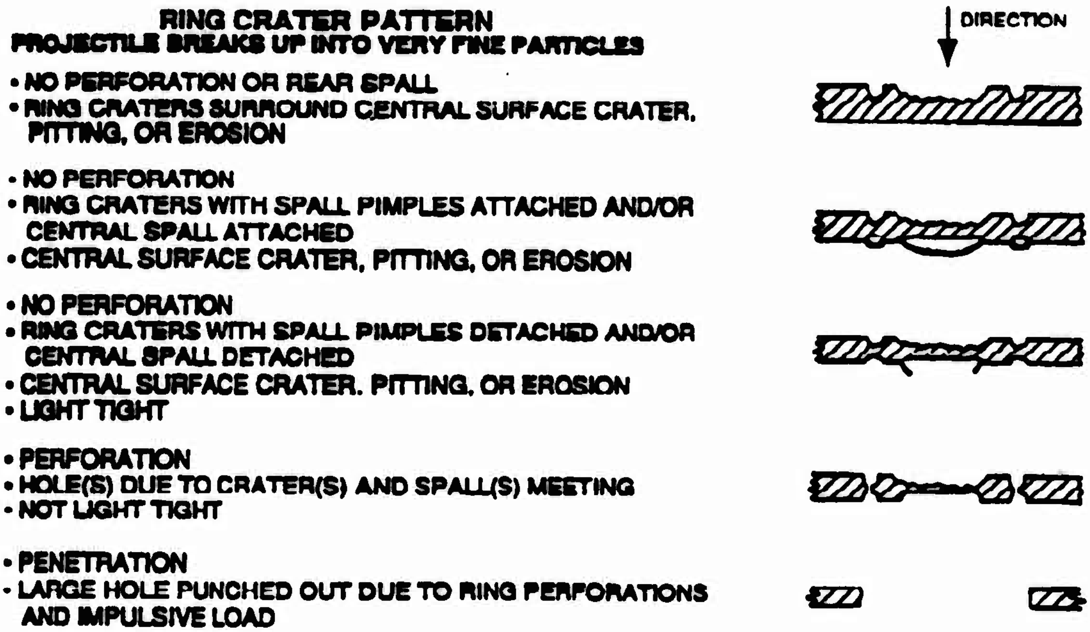

Figure 45. Ring Crater Pattern Damage Classification for Shielded Objects

High velocity particles generated by a penetrating collision can severely disrupt all areas of a satellite. Depending upon the area of impact, they could wreck electronic banks, detonate fuel tanks, or destroy sensors and other equipment. Because of the critical nature of each component on a satellite they are made to be very reliable, ensuring that they work for years. Yet debris collisions with objects as small as 3 mm diameter can cause enough damage to make even robust systems fail completely.

4.2.2. IMPULSIVE LOADING

Impulsive loading occurs on subsequent surfaces after the debris has significantly fragmented upon impact with the skin of the satellite. During such an impact, the debris is fragmented and can liquefy or even vaporize. The resulting numerous small fragments, droplets, and vaporized material generate an impulsive load on secondary surfaces. Large amounts of energy

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[40] Christiansen, E.L. (1991) Meteoroid/Debris Shielding, Phillips Laboratory, NASA and Aerospace Corp. Orbital Debris Technical Interchange Meeting, Kirtland AFB, New Mexico, 2-3 April 1991.

are deposited over a relatively large area compared to the area of the initial impact. Impulsive damage mechanisms include buckling, ripping of surfaces, as well as flexing and bending of the satellite components beyond their limits. Impulsive loading can accompany cratering from individual particles thereby increasing the damage. Spalling is a significant byproduct of impulsive loading as it was with individual impacting particles. Figure 46, also taken from a NASA briefing at the Phillips Laboratory Orbital Debris Technical Interchange meeting, describes the types of damage caused by impulsive loading.[40]

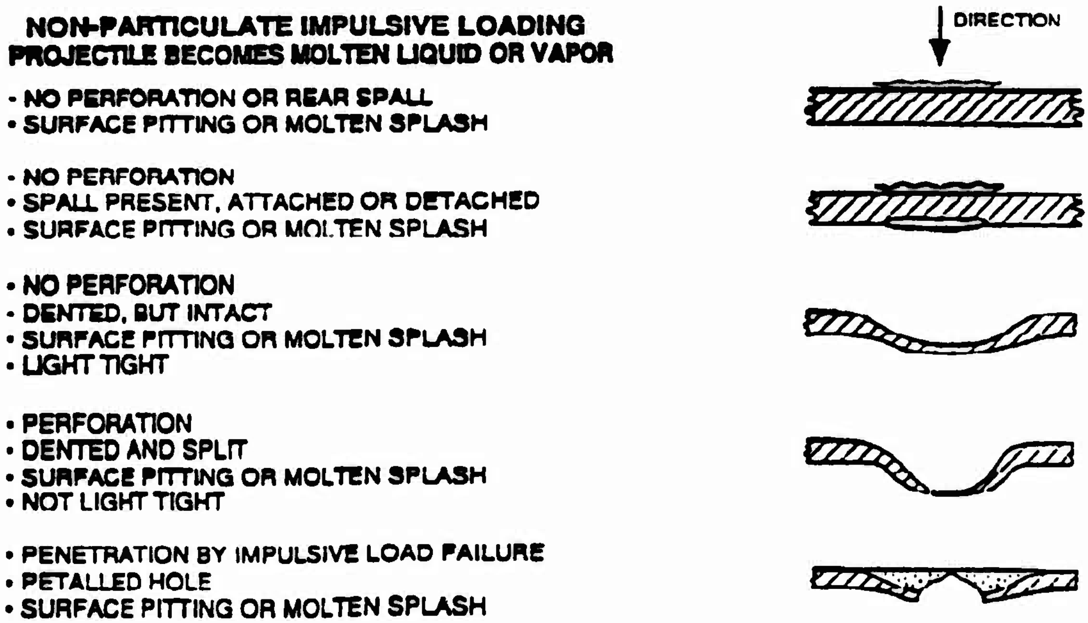

Figure 46. Impulsive Load Damage Classification for Shielded Objects

4.2.3 SPALLING

In high velocity collisions spallation is an important damage mechanism. Spallation creates debris emitted from the back side of an impacted shield or bulkhead. They can have significant velocities and as a result cause additional damage. Spalling is caused by the reflection of the impulsive wave off the back surface of an impacted plate. The back side of the plate releases particles at high velocities, approaching that of the impacting fragments as a result of momentum conservation. These fragments can cause the same damage to internal components as the original debris fragments. They can destroy electronic components, short circuits, and contaminate fuel cells even if the piece of debris has not penetrated the skin of the satellite. Contamination is a major consideration in fuel systems and radiator cooling systems. Contamination with very small spallation pieces can clog the attitude control jets, fuel lines and fuel pumps, since fuel injectors are particularly susceptible to small debris in the fuel.

Another effect of spalling is to decrease the effective thickness of a plate. A crater formed by a particle on the surface and a pit on the backside formed by spalling can join, forming a hole where neither damage mechanism alone would have created one.

4.2.4 SHOCK

Damage within a spacecraft can be caused without a direct impact from fragments or an impulsive wave. A collision with a large debris deposits a significant amount of energy in the spacecraft. Much of this energy is distributed throughout the spacecraft by a travelling shock wave. Energy is transmitted along support structures and other materials, reaching parts of the spacecraft far from the point of collision. Depending on the size of the impacting debris, this shock can cause the total destruction of the spacecraft as it propagates though it. This phenomenon is confirmed by the estimated and observed debris created by on-orbit collisions, such as those done by the United States' anti-satellite weapons tests. Shock waves can additionally cause failure of electronic components, shatter optical components, and destroy antennas and solar arrays.

4.2.5 SECONDARY EFFECTS

Secondary effects of collisions with debris include explosions of spacecraft subsystems such as fuel tanks or pressure tanks that will then cause failure or other damage to the remaining spacecraft systems. The damage to a pressurized compartment may exceed a critical flaw length and result in unstable crack growth or "unzipping". Other failures may be the rupture of a fuel tank or cell resulting in either a detonation or an uncontrolled rapid maneuver that may exceed other performance limits of the satellite.

There are other damage and system failures that can be caused by space debris. The main failure modes for the space station are outlined below. NASA lists the failure modes as:

- Catastrophic Rupture
- Internal Fragments
- Leakage
- Deflagration
- Detonation
- Light Flash
- Pressure Pulse
- Reduced Structural Strength
- Degraded Performance
- Electrical Short
- Long-Term Flaw Growth (Cyclical Loading)
- External Secondary Eject and Penetration Products
- Propagating Failure

Table 12 shows which subsystems are most susceptible to a specific type of damage. This information is taken from a NASA briefing, but it was originally from a 1970 NASA report on meteoroid damage assessment. The information is still valid today.

Table 12. Probable Critical Types of Failure for Various Subsystems

	Subsystems					
Probable Critical Types of Failure	Pressure Cabins	Tanks	Radiators	Windows	Electronics	Special Surfaces
Catastrophic Rupture	x	x		x		
Detached Spalling	x	x	x		x	
Secondary Factures			x		x	
Leakage	x	x	x			
Shock Pulse	x			x	x	
Vapor Flash	x					
Deflagration		x				
Deformation			x		x	
Reduced Residual Strengh	x	x	x	x		
Fluid Contamination		x	x			
Thermal Insulation Damage	x	x				
Obscuration				x		
Erosion				x		x

NASA SP-8042, Meteoriod Damage Assessment, space vehicle Design Criteria (Structures), May 1970 obtained from E.L. Christiansen briefing, Meteor/Debris Shielding, 2 April 1991.

4.3 Hypervelocity Impact Test Results

Many of the effects caused by a collision can be seen in the results of hypervelocity impact tests McDonnell Douglas conducted at the University of Dayton Research Institute. In these tests, pellets of various materials were fired by a gas gun to study pellet impact effects on satellite structural configurations.[41] The tests typically involved 1 gram pellets impacting various shield configurations at velocities of up to 6.4 km/sec. While originally done to study the feasibility of protecting satellites against anti-satellite weapons, these tests also apply directly to the area of orbital debris protection.

In one test a 0.441 gram, 0.5 cm steel pellet impacted at 6.44 km/sec a multiple shield made of six 0.2 cm aluminum plates shown in Figure 47. The first, second, and third shield are penetrated, and the fourth shows significant damage but no penetration. The hole in the first plate is small and clean. The hole in the second plate is significantly larger than the first plate because the pellet fragmented and spread over a larger area as described earlier. The debris impacting the second plate includes the pellet fragments and the mass of the first plate that was punched out by the projectile. The spreading of the fragments and the dispersion angle can be measured by using the pattern left by impacting debris on the second plate.

The third plate has a larger hole and some tearing, which is more characteristic of lower velocities and impulsive loading.[41] The fourth plate received the combination of the fragments from the original projectile and the particles released from the other surfaces, but because the remaining energy was spread over a larger area, the plate was not perforated.

In a similar test, a 0.5 cm diameter, 1 gram pellet of Tantalum was fired at 6.45 km/sec into a similar shield structure made of six 0.2 aluminum plates. Figure 48 shows the results of this test. In this figure, four shields are penetrated and a fifth is significantly damaged. Tantalum has a higher density and boiling point and does not fragment as easily as steel. This resulted in a smaller hole in the second plate and the deeper penetration through the shields.

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[41] McDonnell Douglas Corporation, Space Systems Company, Electronic Systems Company (1990) ASAT Technology -- Lethality, presented to Electronic Systems Division Director of Intelligence, Hanscom Air Force Base, 26 July 1990.

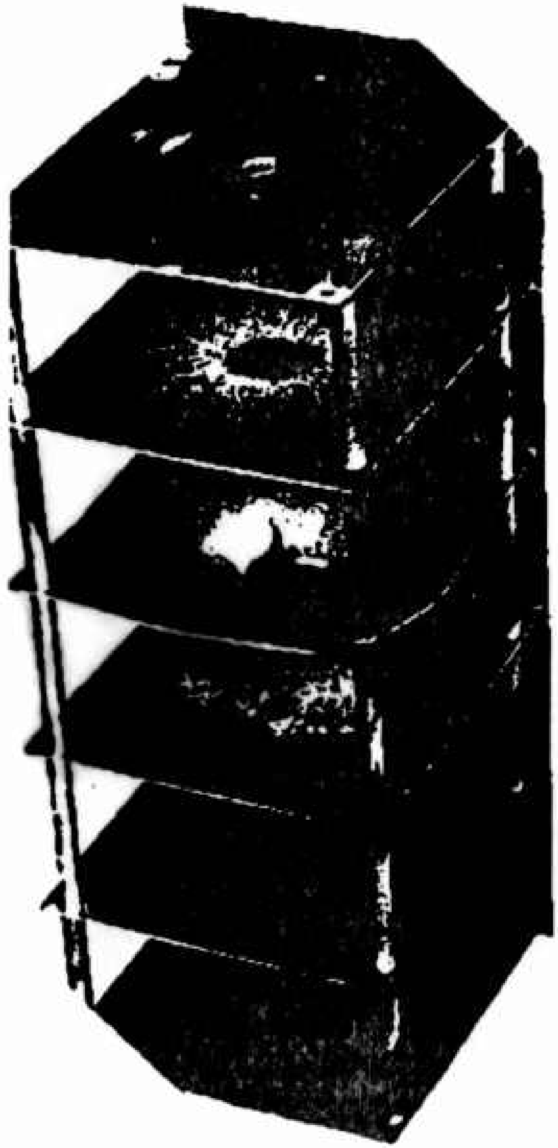

Figure 47. Steel Pellet Impact Test. 0.441 gram, 0.5 cm diameter steel pellet at 6.44 km/sec.[41]

Figure 48. Tantalum Pellet Impact Test. 1.018 gram tantalum pellet at 6.54 km/sec.[41]

In an effort to analyze the effect of pellet mass on penetration depth, two additional tests were run similar to the first steel pellet test, except a 1 gram, 0.635 cm diameter steel pellet and a 0.131 gram, 0.31 cm diameter steel pellet were used. In both tests the fourth plate was penetrated and the fifth plate had dimples and aluminum deposits which had been ejected from earlier plates. These results are very similar to still another test using a 0.44 gram, 0.5 cm diameter steel projectile, indicating that the pellet or debris material is much more important than small changes in the mass of the object when determining penetrating ability.[41] During these tests it is difficult to distinguish between damage caused by fragments from the impacted plates and those of the projectile.

In a further series of tests conducted to study the effects of different impact angles, a 1 gram, 0.5 cm pellet was fired into plates at a 30 degree incident angle (60 degrees off normal), instead of 90 degrees as in the earlier tests. Because of the impact angle of these tests, the projectile fragments traveled further and dispersed more prior to impacting the subsequent plate. This resulted in a significant reduction in the penetration of the fragments. Figure 49 shows the results of this test. On the second plate two impact areas are evident. One area is along the angle of impact and a second is nearly perpendicular to the point of impact. This second impact point is caused by material released from the first plate. The results of this test also indicated that although the third plate was not penetrated, the fourth plate did contain small craters and aluminum deposits caused by spallation from the third plate.[41]

A summary of the tests performed are given in Tables 13 and 14.

Figure 49. Tantalum Pellet Impact Test at 30 Degrees. 1.013 gram Pellet at 6.45 km/sec

Table 13. 90 Degree Impact Tests Results from the University of Dayton Research Institute

Test	Pellet				Plate		Damage
Number	Material	Mass (Gram)	Diameter (cm)	Velocity (km/sec)	Separation (cm)	Thickness (cm)	Last plate penetrated and remarks
1110	Stl	0.441	0.48	6.44	7.6	0.2	3, small bulges in 4.
1116	Stl	1.044	0.63	6.49	7.6	0.2	3, small bulges in 4
1118	Stl	0.441	0.48	6.32	7.6	0.1	3, tear in 4, Aluminum deposits on 5 but not bent
1119	Stl	1.044	0.63	6.54	15.2	0.2	3 small bend in 4
1120	Ta	1.018	0.49	6.54	7.6	0.2	4, Al deposits on 5 - dimpled
1123	Stl	0.131	0.32	6.45	3.8	0.1	3 small hole and bend in 4, 5 dimpledw/Al deposits

Table 14. 30 Degree Impact Tests Results from the University of Dayton Research Institute

Test	Pellet				Plate		Damage
Number	Material	Mass (Gram)	Diameter (cm)	Velocity (km/sec)	Separation (cm)	Thickness (cm)	Last plate penetrated and remarks
1111	Stl	0.441	0.48	6.44	7.6	0.2	2, small dimple in 3
1117	Stl	1.044	0.63	6.59	7.6	0.2	2, bend w/al spalsh on 3
1121	Ta	1.013.	0.49	6.45	7.6	0.2	2 w/severe bend, small holes in 3 w/bend and al deposits, small pocks on 4

It is important to point out that these test were performed to study the possibility of protecting satellites against anti-satellite weapons. Consequently the shields used were much heavier and offer much more protection than what would be used on any space system.

Because of the very high velocities and large kinetic energies involved in collisions with debris, damage caused by even small objects can be catastrophic to space systems. The damage is caused by a number of different mechanism including particle impact, impulsive loading, spalling, and shock. The extent of the damage is a function of the velocity, impact angle, size, and material of the debris. Hypervelocity impact studies done for anti-satellite weapons tests show the dramatic effect of collisions with debris.

5. SPACE SURVEILLANCE SYSTEM

To understand the United States' space surveillance capabilities to measure and track space debris, it is necessary to take a close look at the mission of the Space Surveillance System and the requirements placed upon it. In addition, US Space Command priorities and how these priorities affect space debris measurements, and an evaluation of the radars and optical sensors used to collect the orbital data on the objects critically determine the capabilities of US Space Command. The value of using the Satellite Catalog for space debris measurements will be assessed based on these facts.

5.1 The Space Surveillance System

The United States has established the Space Surveillance System to track, detect, identify, and catalog space objects. The Space Surveillance System is operated by the United States Space Command and its three component commands: Air Force Space Command (which has the main role),[42] Navy Space Command and Army Space Command.

The task of the Space Surveillance System is to identify and classify all detected objects, maintain an accurate and current catalog of them, and provide relevant information to military and civilian agencies and the scientific community.[42] This information includes orbital characteristics, radar signature, and nationality of space objects. The Space Surveillance System consists of the Space Surveillance Network, a group of 29 sensors located around the world; the Space Surveillance Center, located inside the Cheyenne Mountain Complex near Colorado Springs, Colorado; and an Alternate Space Surveillance Center operated by the US Navy, located in Dahlgren Virginia.

The Space Surveillance System provides the following information:

- New space launch detection and tracking information,
- Foreign satellite function identification,
- Satellite maneuver identification,
- Collision avoidance information,
- Data on satellite overflights of specific locations,
- Re-entering objects' impact points,
- Advance warning of attack on US space assets,
- Targeting information for the US anti-satellite system,
- Successful and unsuccessful attack verification information.

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[42] Air Command and Staff College, (1985) *AU-18: Space Handbook*, Maxwell Air Force Base, Alabama: Air University Press, p. 12-10.

The primary method of promulgating this information is the United States Space Command Satellite Catalog. The Satellite Catalog contains information on the identification, origin, orbital parameters, and radar cross section of all identified space objects that are regularly tracked by United States Space Command.

An array of US organizations rely on the Space Command Catalog data to track and operate their satellites, including NASA, NOAA, and the intelligence community. US allies are also given access to the data, since none of our European allies maintain a comprehensive space surveillance network. Instead they rely on our Satellite Catalog to re-establish contact or locate their satellites in the event of a problem during launch or while in orbit.[2] While the European Space Agency has called for the development of such a system for their own use, the cost and complexity has proven prohibitive.[2] The only other country beside the US that maintains a comprehensive satellite catalog is the Soviet Union.

Space Command believes that the sizes of space objects in its catalog range from a wrench dropped by an astronaut to satellites weighing several tons. But the size of space debris that would destroy most space systems in a collision is on the order of one-half centimeter in diameter, significantly smaller than the current detections capabilities of the Space Surveillance System. This is the root cause of the risk created by space debris: it is not possible to detect all the dangerous objects in orbit around the Earth.

The 29 sensors that form the Space Surveillance Network range from older, dish-type, mechanically-steered radars to more modern phased array radars to large telescopes with sensitive, electro-optical detectors. Data collected by these sensors are transmitted to the Space Surveillance Center located inside the Cheyenne Mountain Complex just outside Colorado Springs, Colorado. Here the observations are processed, satellites are identified, and accurate orbital parameters are determined.

The Space Surveillance Center maintains orbital parameters of all cataloged objects. This is done by making routine observations of the satellites' positions and then determining their orbits. Observations are correlated with cataloged objects and orbital parameters are updated. This is known as "maintaining the catalog". If a detected object does not correlate with a previously cataloged object, then additional measurements are made to make a preliminary orbit characterization and determine if it poses a threat to the United States or any of its assets. It is later analyzed to determine its precise orbit, its origin, and its nationality before it is eventually added to the Satellite Catalog. At least this is how the system is designed to work in principle.

5.2 Missions of the Space Surveillance System

There are several missions of the Space Surveillance System. Some have very high priority such as Ballistic Missile Early Warning, satellite orbit prediction, and satellite identification. Others such as space debris measurements, re-entry predictions, and orbital collision warning are designated as secondary missions.

5.2.1 SATELLITE POSITION PREDICTION

To correlate new observations with objects in the Satellite Catalog, to communicate with satellites or to make observations on satellites, the orbit and future positions of the satellites must be known in order to aim antennas and sensors towards any specific satellite. The Space Command Catalog provides the information required to predict the location of all cataloged satellites as a function of time. This information is used by a large number of organizations to download information from satellites and uplink commands to them.

Satellite prediction routines are hampered by the unpredictable effects of the atmosphere, which cause errors that continue to propagate. Over time, these errors will multiply as the satellite's predicted orbit gets farther from its actual orbit. When the errors in the prediction routine get too large, the sensors can not find the satellites that they are attempting to observe. If the satellite is not within a specified range of its predicted position, then additional effort and time must be spent to locate it. This is the reason the Space Surveillance System must continue to make observations of satellites once they have been detected and cataloged to keep the catalog current.

Maintaining the catalog becomes a major problem during periods of geomagnetic activity or solar storms because the atmospheric model used by Space Command to predict the positions of satellites does not model the atmosphere accurately during these periods. Solar or geomagnetic storms can significantly change the atmosphere in low-Earth orbit, especially at high latitudes where much of the energy is deposited. Atmospheric density variations in the polar regions can reach as high as 1000 percent above normal. The increase in density causes an increase in atmospheric drag and significantly changes the satellite orbit from its predicted position. Both in-track (along the line of motion) and cross-track (perpendicular to the orbital plane) variations can occur. High altitude wind velocities in the polar regions can exceed several kilometers per second and can cause significant cross-track errors.

If the Satellite Catalog is not maintained, there can be several consequences. If an active satellite is not near its predicted position and communications cannot be established, then commands to it cannot be transmitted or data cannot be received. Consider a scientific satellite that needs to download data every 24 hours because of a limited on-orbit storage system. If communications cannot be established, older data will either be overwritten or data collection must stop. In either case data is lost. The same may be true of reconnaissance satellites. If operational commands are not received by the satellite, an overflight and observational opportunity may be missed and a chance to observe a specific activity or location is lost.

Maintaining the Satellite Catalog consumes the majority of the Space Surveillance System's resources. To maintain the catalog, each object, depending on the altitude of its orbit, must be observed and accurately tracked every 2 to 10 days. Other satellites whose positions must be known precisely, such as the Global Positioning Satellites, require more frequent observations. Additional observations are required for all low Earth orbiting satellites during periods of increased solar or geomagnetic activities.

5.2.2 SATELLITE IDENTIFICATION/EARLY WARNING

A primary purpose of the Space Surveillance System is the rapid identification of objects detected by the US early warning radars and other sensors. Detected objects are checked against the Satellite Catalog at the radar sites. If the detected object does not match a known object additional measurements must be made in order to identify it and determine if it poses a threat to the United Sates. This allows US Space Command to quickly identify new versus old space objects and determine if there is a military threat posed by the new object, requiring rapid reaction.

The threat US Space Command is most concerned with is an Intercontinental Ballistic Missile attack from the Soviet Union. This is the main purpose of the North American Air Defense Command (NORAD). The Space Surveillance Mission has been inherited by US Space Command from NORAD, which is responsible for Ballistic Missile Early Warning. The US Space Command and NORAD have the same commander. The sensors used to provide information to NORAD are owned and operated primarily by US Space Command.

Other types of threats include those posed by anti-satellite weapons. In the 1980's, the US was very concerned with the operational status of the Soviet anti-satellite system. At that time the role of the Space Surveillance System was to provide rapid identification of an unknown satellite and determine its mission and purpose. If it were an anti-satellite weapon and was expected to engage a United States satellite, quick response would be needed to maneuver the targeted satellite out of harm's way. Also, military and civilian leaders would be notified of a possible attack. This concern has diminished significantly due to the recent changes in the Soviet Union.

Additional considerations require the rapid identification of new satellites and their missions. Different actions must be taken if a newly detected satellite is an intelligence satellite versus a communications satellite. Space Command provides information to a number of organizations, informing them of satellite overflights. This tells organizations when a satellite will be in view of sensors and when they themselves will be in view of a satellite's sensors. They can then direct their sensors to observe the satellite or they can conceal secret activities. The launch of a new intelligence satellite must be quickly identified so that secret activities can be concealed prior to its overflight. Satellite mission identification can be accomplished by using radio emissions, optical imagery, and orbital characteristics.

An example of a Soviet failure to identify a satellite was the KH-11 satellite. This US photographic intelligence satellite transmitted its signals up to other satellites instead of down to ground stations as other intelligence satellites typically did. The Soviets thought this was a dead satellite because it did not emit radio signals that they could detect. Since they thought it was a dead satellite, they did not take the precautions they would have if they knew it was an active intelligence satellite (such as concealing secret activities during overflight). The satellite's purpose remained a secret until the manual for the KH-11 satellite was sold to the Soviets by an ex-CIA operative in 1977.

5.2.3 RE-ENTRY PREDICTION

Another mission of the Space Surveillance System is to predict when objects will re-enter the atmosphere and whether they pose a threat to people or property. The Space Surveillance Center increases the observation frequency of objects as they re-enter the atmosphere so they can predict more accurately the time and location of re-entry. While most of these objects burn-up during re-entry, some survive and impact the Earth's surface.

Another reason for keeping track of spacecraft re-entering the atmosphere stems from the 1967 United Nations Space Treaty that makes each country absolutely responsible for damage done by their returning spacecraft. Space Command closely monitors any object that is large enough to possibly survive re-entry and impact the Earth. This reasoning may some day be extended to include damage to other space systems by debris. These legal aspects of space debris will be covered in a later section.

5.2.4 COLLISION AVOIDANCE

The Space Surveillance Center also provides collision avoidance alerts to high priority systems such as the Space Shuttle and specialized satellites. These alerts are issued whenever a cataloged object is predicted to pass within a certain range of the spacecraft. This warning would allow for orbital maneuvers that could limit the chance of collisions. Examples of this occurred in September and November 1991 when the Space Shuttle made small orbital maneuvers to avoid used Soviet rocket boosters after being alerted by the Space Surveillance Center. Shuttle launch profiles are also checked before each mission for possible collision paths. This collision avoidance mission will become significantly more important as the space debris environment continues to grow and the frequency of close approaches increases.

5.3 The Space Surveillance Network

The Space Surveillance Network uses radars, telescopes, cameras and radio receivers to make 30,000 to 50,000 satellite and debris observations each day. These observations are correlated with the Satellite Catalog at each sensor site. Orbital measurement observations of certain satellites and uncorrelated objects are transmitted to the Space Surveillance Center to update the Satellite Catalog and to correlate the observations with other uncataloged objects.

To keep track of the 7,000 objects that are currently in the catalog, Space Command relies on a number of different optical and radar sensor systems located around the world. The typical ranges and detectable sizes for radar and optical systems are shown in Figure 50. Radars are typically used for low-Earth orbit satellites and optical systems are typically used for high-Earth orbit and geostationary orbits. The locations of the systems used in the Space Surveillance Network are shown in Figure 51. A full listing of these systems is provided in Table 15 at the end of this section.

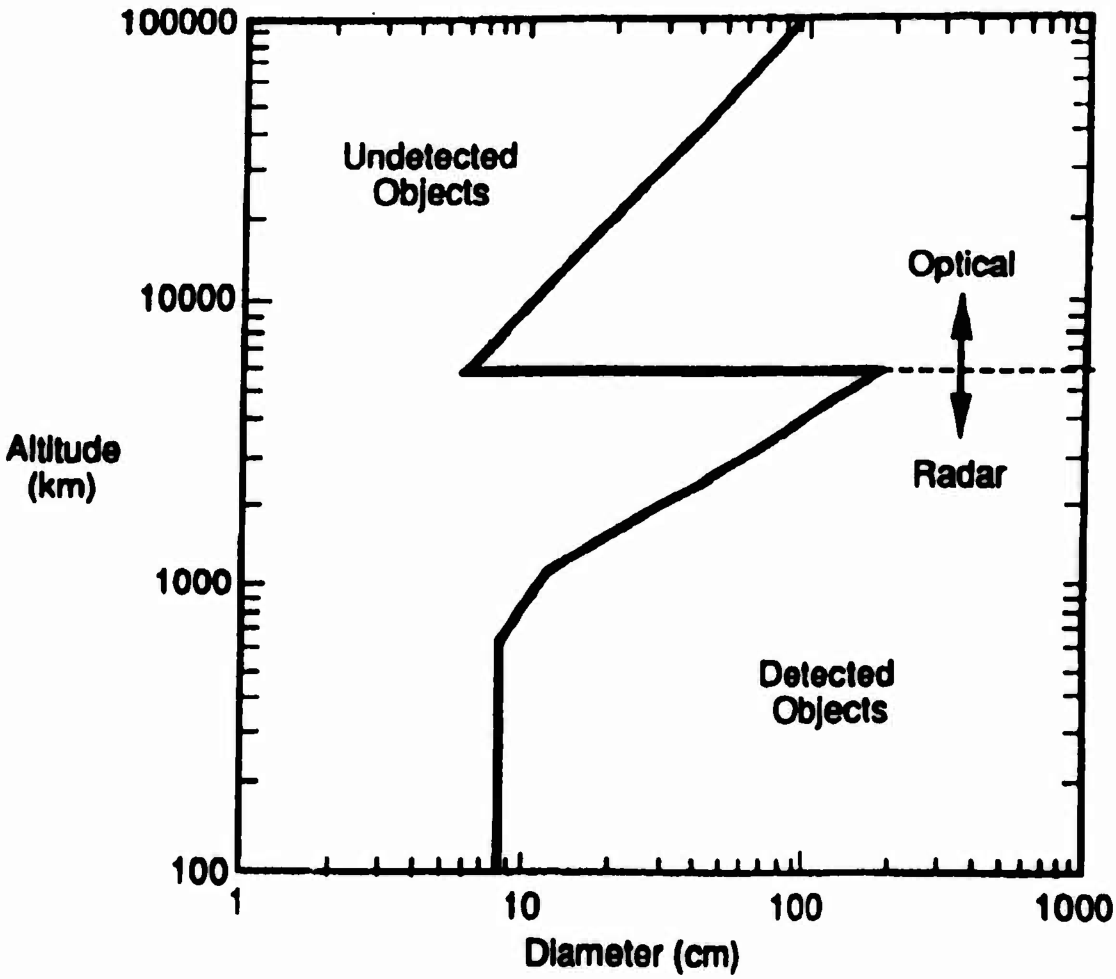

Figure 50. Detection Capability of Space Command Radar and Optical Systems[17]

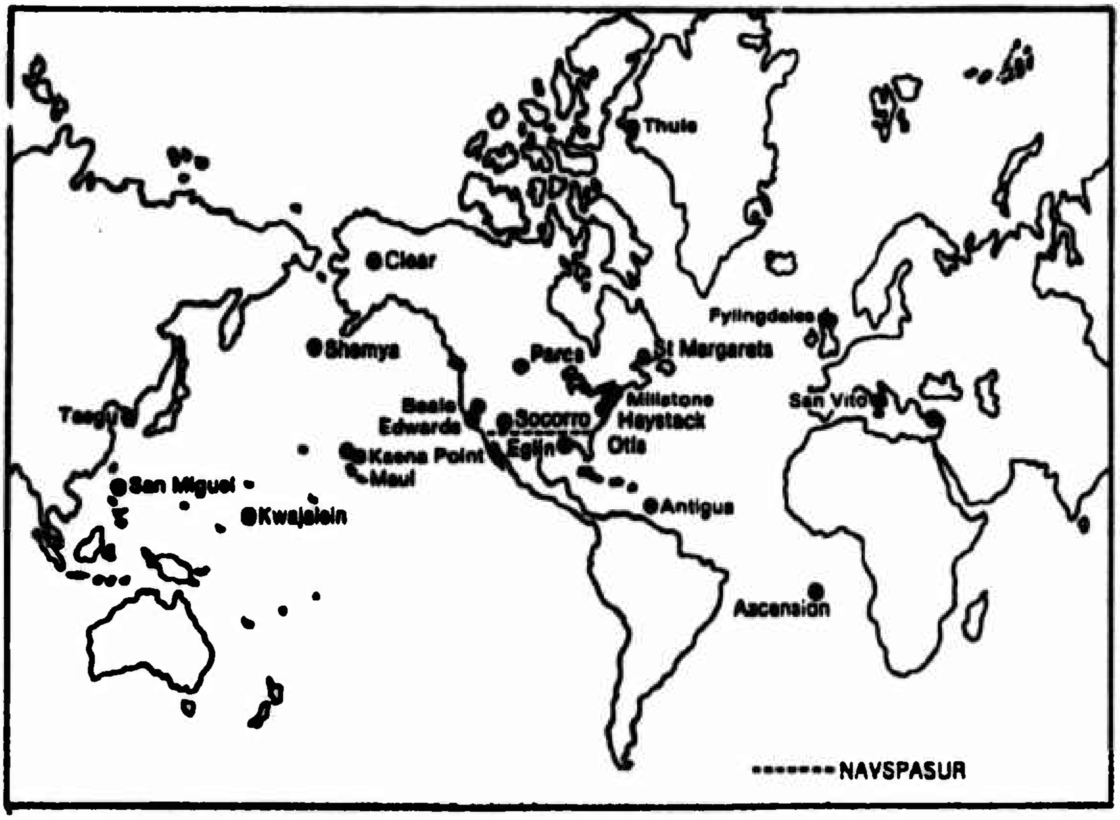

Figure 51. Location of the Sensors in the Space Surveillance Network[42]

In order to determine the capabilities of the Space Surveillance Network it is important to analyze the performance of the individual sensors used in it.

5.3.1 RADAR SYSTEMS

US Space Command operates a large number of radar systems, the majority of which are designed to provide early warning of a ballistic missile attack on the United States. These radars include modern, phased- array radars, fixed beam fan radars, and steerable dish antennas. The main dedicated sensor for space surveillance is the Naval Space Surveillance System Fence.

5.3.1.1 Naval Space Surveillance System

The primary radar system in the Space Surveillance System is the Naval Space Surveillance System (NAVSPASUR). This system was built in response to the Soviet launch of

Sputnik and became operational in 1959. Since then the system has been updated, but the operational principle has changed little. NAVSPASUR consists of three transmitter and six receiver systems. The three transmitters form a fan or "fence" of energy across the United States from Georgia to California. When objects cross this fence they reflect its radio waves. These reflected radio waves are then detected by a number of receivers. This provides some orbital data on all detected objects crossing the fence. The data includes the altitude, time and location where the object crossed the fence and an approximate radar cross section. This system is not used to make observations of specific objects as most other radar systems are. Given the radio power, the vast area the fence covers and the sensitivity of the receiver system, this system is currently limited to detecting metallic objects on the order of 30 cm or larger.[43] The NAVSPASUR fence usually provides the first indication of a satellite or rocket body breakup.

5.3.1.2 FPS-85

The FPS-85 radar system is located at Eglin Air Force Base, Florida and is the Air Force's most powerful phased array radar system. This system's mission is dedicated to the space surveillance mission, the detection of sea launched ballistic missiles (SLBMs) fired from the Gulf of Mexico, and intermediate range ballistic missiles (IRBMs) launched from Cuba. Even though it is an older phased array radar, beams of this system have the highest power density. And, although it does not include many of the modern receiver features of the PAVE PAWS radar system, its high power output makes it particularly effective in looking for small debris.

5.3.1.3 Early Warning Radars

In addition to the Navy's NAVSPASUR system, the Air Force operates a large number of missile warning and missile test monitoring radars. These systems include the older Ballistic Missile Early Warning System (BMEWS) and the more modern, phased array radar systems such as the PAVE PAWS. These systems are placed strategically around the United States and the world to provide advanced detection of Soviet intercontinental ballistic missile (ICBM) launches. As a result of observations looking for ICBM launches, these systems see satellites and debris that are reported to the Space Surveillance Center.

5.3.1.3.1 Perimeter Acquisition and Attack Characterization System

The Perimeter Acquisition and Attack Characterization System (PARCS) located at Concrete, North Dakota is also one of Space Command's most powerful radars. As its name implies, it is designed to characterize a nuclear attack on the United States, but is also able to

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[43] Improving the fence, (1991) *Space Tracks*, Naval Space Command , January-February 1991.

perform some space surveillance functions for the Space Surveillance Network. During specialized tests this system can detect objects as small as 8 cm or less. [44]

5.3.1.3.2 Ballistic Missiles Early Warning Radars (BMEWS)

The BMEWS radars were built in 1960. They have long-range fan type beam patterns formed by their fixed elongated antennas and are intended to provide the first indications of a Soviet ICBM attack over the North Pole. They observe a wide angle of sky, and they can detect many objects simultaneously.

5.3.1.3.3 COBRA DANE and the AN/FPS-79

COBRA DANE and the AN/FPS-79 radars are employed to monitor Soviet ICBM tests. They are large phased array radar systems with a range reported to be 40,000 km.[45] But Air Force Space Command reports the effective range as about 5,500 km.[46] COBRA DANE is an L-band radar system and is located at Shemya, Alaska in the Aleutian Islands. AN/FPS-79 is an ultra-high frequency (UHF) radar system and is located in Pirinclik, Turkey.

In addition to these sensors there are a number of other radar systems that can be used to track space objects, if required. These include the tracking radars used at the Eastern Test range at Cape Canaveral, Florida, those used at the Western Test Range at Vandenburg AFB, California, and those in the Kwajalein Atoll in the South Pacific. Another specialized system that can be used for debris tracking is the Haystack radar for deep space operations, which is operated by Massachusetts Institute of Technology in Massachusetts. Haystack is currently being used by NASA for observing space debris.

5.3.2 OPTICAL SENSORS

In addition to radars that illuminate their targets with electromagnetic radiation, there are also passive optical systems that rely on reflected sunlight to illuminate objects. These systems are limited in their hours of operation because the satellite must be illuminated by the sun and be in view of the optical sensor while it is in the dark. For low-Earth orbit objects, this occurs near the dawn or dusk terminator periods. This limited time restricts the value of all optical systems for

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[44] United States Air Force Scientific Advisory Board, (1987) *Report of the Ad Hoc Committee on Current and Potential Technology to Protect Air Force Space Missions from Current and Future Debris*, United States Air Force Scientific Advisory Board.

[45] Stares, Paul B. (1987) *Space and National Security*, The Brooking Institution, Washington, D.C.,

[46] Jackson, P. (1990) Space surveillance satellite catalog maintenance, Article AIAA 90-1339 from the AIAA/NASA/DOD Orbital Debris Conference: Technical Issues & Future Directions, 16-19 April 1990, Baltimore, Maryland.

debris characterization. The available time for tracking higher altitude satellites is significantly longer. Because of this fact, optical systems are currently used to track high altitude objects--those over 5000 km.[44] The minimum detectable size of an object depends heavily on its reflectivity, which can vary by as much as a factor of 10.[44]

5.3.2.1 Ground-Based Electro-Optical Deep Space Surveillance Systems

The Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) Systems are the primary surveillance systems used by Space Command. There are currently four operational sites, and a fifth is awaiting installation. These systems are at various sites around the world in order to provide regular coverage of most orbits.

A GEODSS system consists of two 40-inch telescopes for deep space observations and a smaller, wider angle 15-inch telescope for near-earth applications. These telescopes focus the image on a vidicon television camera system. The stars are subtracted and the resulting image is displayed on a video console. Satellites appear as streaks across the monitor. The electro-optical system allows for rapid processing so position and identification data can be transmitted to the Space Surveillance Center in seconds.[47]

5.3.2.2 Baker-Nunn Cameras

Two large aperture camera systems were used since 1956 to provide deep space surveillance prior to the development of the GEODSS system. Built in 1956, these sensitive cameras provided satellite tracking out to 80,000 km altitude. The two sites, located in Canada and Italy, provided coverage for most of the geosynchronous ring. These systems used high speed film and required hours of processing and interpretation before the information was sent to the Space Surveillance Center. These deficiencies have been corrected with the new electro-optical system of the GEODSS telescopes.

5.3.2.3 Other Optical Systems

Another optical system utilized for space surveillance and imaging is the Maui Optical Tracking and Identification Facility (MOTIF) located on Mt Haleakala, Maui. This system is used to identify the shape and hence the mission of foreign satellites. It is co-located with the Advanced Maui Optical Site and a GEODSS site. Another optical system is the Teal Amber site at Malabar, Florida. Further advances in spacecraft imaging utilizing adaptive optics have been made by

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[47] United States Space Command, Directorate of Public Affairs, (1988) *Fact Sheet: The U.S. SpaceCommand Space Surveillance Network*, United States Space Command, Peterson Air Force Base, Colorado.

Phillips Laboratory at the Star Fire Optical Range near Albuquerque, New Mexico. These new systems have only recently been declassified.[48]

5.4 Detection Capability of the Space Surveillance System

5.4.1 RADAR DETECTION LEVELS

Several factors determine the minimum detectable size of objects that Space Command's radars and optical systems can find. For radar systems, the primary considerations are the gain of the antenna, the frequency band the system is operating at, the power output of the transmitter, and the range to the target. A simplified expression that gives the cross section of the smallest detectable object is, quite generally, given by Eq. (4).

$$\sigma = \frac{(4\pi)R^4\lambda^2L(S/N)kT_s}{P_{avg}A_e^2t_{ot}} \tag{4}$$

where:

σ = radar cross section of the smallest detectable object (m^2)
R = range to target (m)
λ = wavelength of the radar (m)
L = losses
S/N = required signal to noise for detection
k = Boltzmann's constant (J/K)
T_s = system noise temperature (K)
P_{avg} = average transmitter power (Watts)
A_e = equivalent area of the antenna (m^2)
t_{ot} = time on target (sec)

The radar cross section of small objects is a function of the radar wavelength. Figure 52 shows the cross-section of spheres of various sizes at different wavelengths. The oscillating effect on the X and Ku bands is a result of interference caused by the shape of the sphere and can be neglected for typical debris.[49] Because of the rapid decrease in the radar cross section with a

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48 Discussed in open session with Colonel Marchiando, Commander of Air Force Phillips Laboratory, 16 July 1991.

49 Beusch, J., and Kupiec, I. (1990) NASA debris environment characterization with the

decrease in an object size (as illustrated in Figure 52). L-band and UHF radars are not particularly suitable for detecting debris smaller than 3 cm. Newer experimental X-band and K_u-band radars that can detect smaller debris are being developed, but the high power transmitters and high gain antennas are significantly more expensive than traditional L-band radars and will require a significant amount of money to become operational.

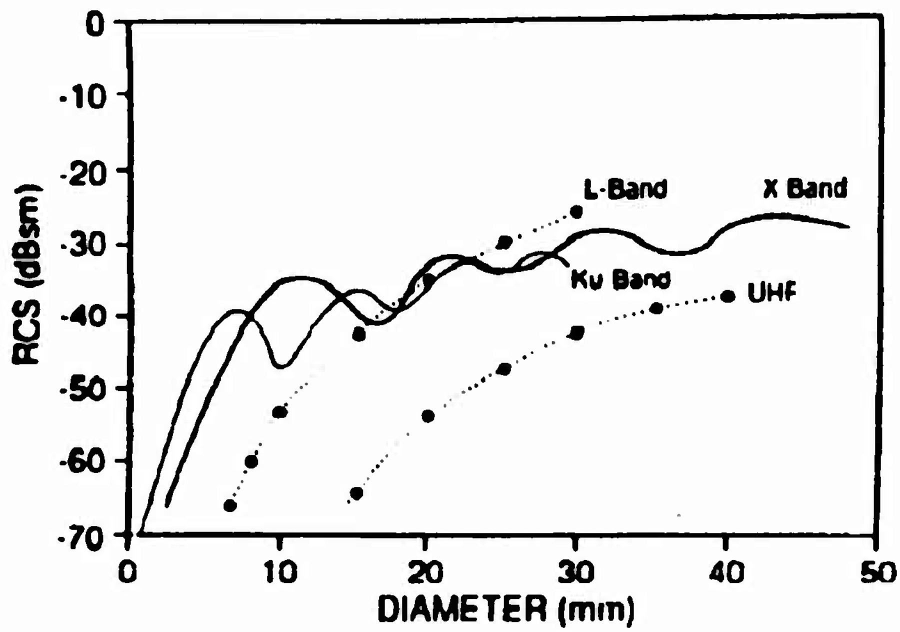

Figure 52. Radar Cross Section of Spheres as a Function of Diameter[49]

5.4.2 OPTICAL DETECTION LEVELS

For optical systems the signal level for modern detection systems is given by Eq. (5)

$$S_{Object} = \frac{A\ QE\ \tau\ F_{Sol}\ Alb\ F(\theta)\ \sigma_{opt}}{R^2} \tag{5}$$

Haystack radar, Article AIAA-90-1346 from the AIAA/NASA/DOD Orbital Debris Conference: Technical Issues & Future Directions, 16-19 April 1990, Baltimore, Maryland.

where:

σ_{opt} = the optical cross section (m^2)
A = the telescope area (m^2)
QE = the quantum efficiency of the detector system
τ = the signal integration time (sec)
F_{Sol} = the solar flux in the band in which the detector is sensitive (Watts/m^2)
$F(\theta)$ = phase function - fraction of illuminated object visible
Alb = albedo of the object (ratio of the incident light to reflected light)
R = the range to the object (m^2)
(S/N) = the signal to noise ratio required to detect the object

The background signal is given by Eq. (6)

$$S_{background} = A\ QE\ \tau\ \phi_{pxl}^2 L_{bkg} \tag{6}$$

where:

ϕ_{pxl} = the angle viewed by each pixel (deg)
L_{bkg} = the background light (Watts/m^2 deg^2)

Since the signal to noise ratio is given by

$$S/N = \frac{S_{Object}}{\sqrt{S_{background}}} \tag{7}$$

The minimum optical detection level is given by:

$$\sigma_{opt_{min}} = \frac{R^2 \phi_{pxl} \left(L_{bkg}\right)^{0.5} \left(S/N\right)^{0.5}}{\left(A\ QE\ \tau\right)^{0.5} F_{sol}\ Alb\ F(\theta)} \tag{8}$$

Note that with optical systems, the signal decreases as a function of the range squared, not as a function of the range to the fourth power as it does with radars. This makes optical systems more sensitive at longer ranges. Another consideration is the angular rate that the object image crosses the detector. For non-tracking telescopes where the telescope is not locked on to the object's motion, the image is spread over several pixels, thus decreasing the available signal for discrimination against the background level.

5.4.3 SIZE DETERMINATION OF SPACE OBJECTS

To determine the size of a detected object (either through optical or radar systems) several key problem must be solved. Both systems rely on the correlation between size and the radar or optical cross section. This correlation depends on the shape, size, and material characteristics of the object. Radar cross sections from a piece of insulation broken off of a satellite will appear much smaller than its actual size, while metal cables will produce much larger signal returns. Tracked objects' radar cross sections can vary over an order of magnitude or two depending on their orientation to the radar as they tumble and spin.[50]

Many of the same considerations must be taken into account for optical measurements. The size of the object; the solar angle between the object and the sensor; and the albedo and the orientation of the object all play a critical part in the optical signal received. Other considerations are the atmospheric conditions and the ability of the detector system to accurately take optical cross section measurements. NASA analysis indicates that an average albedo for space debris objects is 0.08 as determined by hundreds of measurements.[29] NASA has run many tests to correlate radar cross sections with optical cross sections and has found that the two do not correlate well. These were done at simultaneous tests at the Kwajalein Atoll.[29] The analysis of these tests indicated that there was a factor of 2 to 4 difference between the size of the object determined by radar and optical means. The difference may be due to differences in materials with different albedo and radar reflectivities. Consider, for example, a large piece of insulation which may have significantly different optical and radar cross sections. The insulation may return a large optical signature because it has a high albedo, but it may have a very small radar cross section because it is not metallic and does not reflect the radio waves efficiently. The opposite example is a wire or corner reflector that will reflect radio waves very efficiently and yet have a small optical crosss section.

The uncertainties in the radar cross sections is another consideration when trying to compare them with optical cross sections. Radar cross section measurements are made with the FPS-85 phased array radar system at Eglin Air Force Base, Florida. This system is said to systematically under-estimate the radar cross section by 2.3 dB due to an erroneous scaling factor. This corresponds to a factor of 1.7 in size.[51] The lessons learned from these studies is that any correlation made between optical and radar cross sections and the size of an object is a rough approximation and should not be considered an exact measurement.

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[50] Badhwar, Gautam, and Anz-Meador, Philip (1990) Relationship of radar cross section to the geometric size of orbital debris, Article AIAA-90-1347 from the AIAA/NASA/DOD Orbital Debris Conference: Technical Issues & Future Directions, 16-19 April 1990, Baltimore, Maryland.

[51] Badhwar, Gautam, and Anz-Meador, Philip (1990) On-orbit breakup characteristics, Article AIAA-90-1359 from the AIAA/NASA/DOD Orbital Debris Conference: Technical Issues & Future Directions, 16-19 April 1990, Baltimore, Maryland.

5.5 Conclusion on Space Surveillance System Capabilities

In conclusion, United States Space Command's Space Surveillance System is a very effective system for tracking large space objects. It maintains a large array of sensors and systems that track a wide variety of objects in space. It performs its early warning functions in a reliable manner. However, it has significant problems tracking smaller but equally dangerous debris. The current debris size limit is at least one and possibly two orders of magnitude larger than those objects considered lethal even to shielded spacecraft. The limit of size capable of being cataloged, about 10 centimeters, is a result of the available sensors. It is not based on a realistic assessment of the potential hazardous debris present to active satellites. Use of the Satellite Catalog for space debris predictions and modelling must take these considerations into account.

Table 15. US Ground-Based Space Surveillance Systems

Name	Sites	Sensor Type and Designation	Initial Operational Capability	Primary Mission	Range (km)
Dedicated Sensors					
NAVSPASUR (Naval Space Surveillance System)	Lake Kickapoo, TX Gila River, AZ Jordan Lake, AR	Transmitters Continuous Wave	1959	Satellite Tracking	8,100
	Ft. Stewart, GA Silver Lake, MS Red River, AR Elephant Butte, NM San Diego, CA Hawkinsville, GA (HQ Dahlgren, VA)	Receivers	1959		
PACBAR (Pacific Barrier Radar)	San Miguel, Philippines	MSR (GPS-10) C-Band	1983	Satellite Tracking	2,500
	Saipan	MSR (GPS-10) C-Band	1990		2,500
Baker-Nunn	San Vito, Italy St. Margrets, Canada	Optical 40-in Telescope, Film	1956	Satellite Tracking	80,000
GEODSS (Ground Based Electro-Optical Deep Space Surveillance)	Socorro, NM Haleakala, Maui, HI Taegu, Rep of Korea Diego Garcia	Electro-optical Telescopes (two 40-in; one 15 in.) Visible	1981 1982 1982 1986	Satellite Tracking	35,000
MOTIF (Teal Blue) (Maui Optical Tracking Identification Facility)	Haleakala, Maui, HI	Electro-Optical Telescopes Visible, LWIR	n.a.	Satellite Tracking	35,000
Teal Amber	Malabar, FL		n.a.		

Table 15. US Ground-Based Space Surveillance Systems (Cont.)

Name	Sites	Sensor Type and Designation	Initial Operational Capability	Primary Mission	Range (km)
Collateral Sensors					
AN/FPS-85	Eglin AFB, FL	LPAR - UHF	1975	SLBM early Warning	3,500
BMEWS (Ballistic Missile Early Warning System)	Thule AB, Greenland	MSR (FPS-49A FPS-50)	1960	Missile Warning	4,000
	Fylingdales, U.K.	MSR (FPS-49; FPS-50) UHf	1960		5,555
	Clear AK	MSR (FPS-50; FPS-92 UHF	1960 n.a.		5,555
Cobra Dane	Shemya Island. AK	LPAR (FPS-108) L-Band	1977	Missile Test Monitoring	5,555
PARCS (Perimeter Attack Radar Charac-teriazation System)	Cavalier, ND	LPAR - UHF	1974	Missile Warning	3,200
AN/FPS-79	Pirinclik, Turkey	MSR (FPS-79) UHF	n.a.	Missile Test Monitoring	4,300
Pave Paws	Beale AFB, Beale, CA Otis AFB, Cape Cod, MA Robins AFB, Robins, GA Goodfellow AFB, Eldorado, TX	LPAR (FPS-115) UHF LPAR (FPS-115) UHF LPAR (FPS-115) UHF LPAR (FPS-115) UHF	1980 1980 1987 1988	Missile Warning	5,555

Table 15. US Ground-Based Space Surveillance Systems (Cont.)

Name	Sites	Sensor Type and Designation	Initial Operational Capability	Primary Mission	Range (km)
Contributing Sensors					
Eastern Test Range (ETR)	Antigua Island	MSR (FPQ-14) C-Band	n.a.	Launch Support	2,300
	Ascension Island	MSR (FPQ-15) C-band	n.a.		1,600
Western Test Range (WTR)	Kwajalein Atoll	ALCOR C-Band	1972	Launch Support	5,555
		ALTAIR C-Band	1981		40,000
	Kaena Point, HI	FPS-16	1980		n.a.
	Vandenburg AFB, CA	FPS-16	n.a.		n.a.
Millstone	Millstone Hill, MA	MSR L- Band	n.a.	Satellite Tracking	35,000
Haystack	Millstone Hill, MA	X-Band	n.a.	Satellite Tracking	35,000
AMOS (Maui Optical Station)	Haleakala, Maui, HI	Electro-Optical Telescope Visible, LWIR	n.a.	Satellite Tracking	35,000
SITU	St Margarets, Canada	Visible	n.a.	Satellite Tracking	35,000

MSR = Mechanically Steered Radar LPAR = Large Phased Array Radar
n.a. = Not available LWIR= Long Wave Infrared

Sources: Stares, Paul B. *Space and National Security*. The Brookings Institution, Washington, D.C., 1987
Jackson, Major P. Space surveillance satellite catalog maintenance. Article AIAA 90-1339 from the AIAA/NASA/DOD Orbital Debris Conference: Technical Issues & Future Directions. 16-19 April 1990. Baltimore, Maryland.
Air Command and Staff College. *AU-18: Space Handbook*. Maxwell Air Force Base, Alabama: Air University Press, January 1985.

6. SPACE DEBRIS RESEARCH EFFORTS AND MEASUREMENTS

There are several groups doing research in the field of space debris. The three key agencies in the United States are NASA, Air Force Space Command, and the Air Force Phillips Laboratory. The current government space debris research efforts were developed as a response to the Interagency Group (Space) report in 1989.[52] From this the National Security Council directed both the Office of the Secretary of Defense and NASA to develop a plan to address the issues raised in the report. The Air Force was selected as the lead service in this DoD effort. The Phillips Laboratory and its various directorates, formed to be the focal point for all Air Force space research, guides the Air Force effort. NASA's Johnson Space Flight Center was designated the primary NASA center for space debris studies.

Phillips Laboratory and NASA/Johnson Space Flight Center developed a joint plan of research that avoided excessive duplication of effort. This plan was approved by the National Space Council in July 1990. Phase I of the research to be carried out in FY 90-92 consisted of the following activities:

- Assess the orbital debris environment
- Develop Space Station Freedom design criteria
- Document debris minimization practices and procedures
- Provide design concept studies and tool development for spacecraft survivability
- Support development of standards, national policy, and international agreements regarding the space debris environment.

Phase II is to continue research and joint debris minimization activities and other activities depending on Phase I results.[53]

This research raised three peacetime issues for the military. The first was that ignorance of the current orbital debris environment was due to the lack of adequate tools to assess the threat to Department of Defense space operations. The second issue was that there was a very limited or no ability to predict the long term space debris environment and the consequences associated with an unstable debris environment. The last issue was that national policy and international agreements will directly impact DoD space operations in terms of the design, deployment, and testing of future space systems.

Although all three organizations involved in space debris measurement are working together in an attempt to provide a complete understanding of the space debris environment and solutions to

[52] National Security Council, (1989) *Report on Orbital Space Debris*, National Security Council Interagency Group (Space).

[53] Phillips Laboratory, (1991) Space Debris Research Program Agenda, briefing presented at the WS Program Review, June 1991.

the growing threat of space debris, each has a different set of requirements they are trying to achieve.

NASA is primarily interested in space debris because of the International Space Station Freedom and the threat to it posed by space debris. NASA has produced long term space debris population models and engineering models. These models have focused on the requirements for the Space Station.

Phillips Laboratory's goal is to determine the long term space debris effects on DoD operations and how space debris may affect future weapons systems such as the Strategic Defense Initiative. Its role focuses on the current debris environment, the peacetime issues associated with the present debris environment, as well as war time and battle engagement questions associated with the use of anti-satellite weapons and future anti-ballistic missile systems. Effects on sensor systems, the viability of discrimination of targets and debris, and the feasibility of damage assessment are all part of the Phillips Laboratory research program.

US Space Command is concerned with the space debris problem for a number of reasons. Space Command has a basic role to play in all space debris research: because it is responsible for tracking all space objects, it must have a clear view of what already exists in space. Its key mission is to provide early warning of attack on the United States by quickly identifying unexpected and uncataloged objects in space. Another part of its mission is to provide warning of an impending collision to critical satellites and space systems. It must determine methods and requirements to accomplish this mission for ever smaller debris. To accomplish this mission, significant upgrades in satellite tracking capabilities must be developed. Space Command has focused on the problems of tracking and cataloging debris. Space Command prefers to have each object individually identified and its orbit determined. It has been very reluctant to deal with orbital debris in a statistical manner.

Space Command has the primary responsibility to provide space support to US military units around the world. It has taken over a number of satellite systems from Air Force Systems Command such as the Global Positioning Satellites. Over time Space Command will assume responsibility for most Department of Defense space systems. US Space Command will also have the primary role in any type of space-based Strategic Defense Initiative systems that space debris would threaten. Consequently the near-Earth debris environment is very important for this Air Force Command.

Phillips Laboratory, NASA and United States Space Command all have measurement programs designed to address their different objectives. To date, cooperation between the three organizations has been good. Phillips Laboratory has been working closely with NASA and US Space Command and has often acted as the coordinating agency. US Space Command has provided radar and optical tracking data to NASA. While there have been several issues between the organizations, these problems have been minor and have not hampered significantly the flow of information or cooperation.

6.1 US Space Command Debris Measurement Programs

US Space Command had begun investigating the possibility of several space debris measurement efforts. These typically involve special configurations of their existing radar and optical systems. Most efforts are aimed at determining the completeness of the Satellite Catalog and identifying steps required to catalog additional objects. Space Command has indicated that they are not interested in a statistical analysis of the debris environment but require orbital parameters on each object in order to correlate them with known objects or to eventually include them in the Satellite Catalog.

6.1.1 FPS-85 RADAR FENCE

Space Command's primary debris research program uses the Eglin Air Force Base FP-85 radar system to form an electronic fence and track debris as it passes though the radar beam pattern. In order to devote the full power to the debris measurements, the system would need to be taken off its normal mission of space track operations and searching for hostile missile launches from Cuba and submarines. The beam could form a fence 15 degrees in width at 70 degrees above the horizon that would detect objects crossing it. Although the actual radar characteristics are classified, Eglin's FPS-85 is one of the most powerful phased array radars in the United States. Space Command officials familiar with the FPS-85 system believe that it could observe debris as small as 3 cm at the lowest orbital altitudes.

Since the FPS-85 is a phased array radar, a part of its beam could be diverted to track an object detected by the fence to make an initial orbit determination. The initial orbit determination could then be used to direct other sensors to make observations of the object and then include it in the Satellite Catalog. This radar then is ideally suited for the task of enlarging the catalog with smaller orbital objects.

6.1.2 PAVE PAWS RADARS

The Air Force operates several phased array radar systems known as PAVE PAWS. These radars are not as powerful as the one at Eglin, but have significant capability for detecting space debris. Their primary mission is to detect sea-launched ballistic missiles. This mission however does not require the full power of the radar systems. Space Command officials estimate that fully 60 percent of the available radar power could be made available for space debris measurements without detracting from the primary mission. These systems could be used to collect additional data on the larger space debris population. Space Command officials estimate that these radar systems could detect objects on the order of 5 cm at the lowest orbital altitudes.

Other considerations may be to have the PAVE PAWS systems conduct more of the daily Satellite Catalog maintenance missions and have the more powerful radars concentrate on the more difficult smaller debris.

6.1.3 GEODSS SITE OPTICAL MEASUREMENTS

Air Force Space Command has been collecting some space debris data with its GEODSSfacilities at Diego Garcia and Hawaii for NASA. These data indicate that the Space Command Catalog underestimates significantly the number of particles between 5 and 20 cm. Although Space Command has shown skepticism in the satellite correlation process used, this data led to an analytical expression (the HENIZE function) now used in the models NASA uses for the Space Station design.

GEODSS sites are currently under-utilized due to funding shortfalls, with several of the GEODSS sites operations being scaled back due to operational budget cuts. Many sites will be operating only one of their two telescopes on a routine basis.

Additional capability also exists and is unused. The fifth GEODSS site meant for Portugal has not been (and does not look like it ever will be) installed. This equipment is in mothball status at the Lincoln Laboratory facility at Socorro, New Mexico. With reasonable funding, and the proper approvals from Air Force Systems Command, measurements could be made utilizing its capability with the crews already on contract with the Phillips Laboratory.

6.2 NASA Space Debris Research Program

NASA's space debris effort has been driven by the requirements of the International Space Station Freedom. NASA has concentrated its efforts in developing a number of models to predict the long-term growth of space debris and engineering models to aid in designing the Space Station to be protected from space debris.

6.2.1 NASA SPACE DEBRIS MODELLING PROGRAM

NASA's space debris modelling effort is centered at the Johnson Space Center. NASA's modelling efforts goals have been the characterization of the space debris environment and its long-term growth. Models include the comprehensive Evolutionary Model (Evolve) and a simpler engineering model. The Evolve Model includes variables such as the space launch rates, on-orbit breakups, atmospheric decay and on-orbit collision models. It also includes measurements from Solar Max, GEODSS, and US Space Command Satellite Catalog.[25] The engineering model interpolates output from the Evolve code to provide an easy to use model that incorporates the most significant variables of altitude, inclination, time and date, solar activity, impacting size, velocity, and direction.[37]

The limiting factor in these models are the small amount of actual space debris data on which they are based. Uncertainties in some altitude regions are one to two orders of magnitude. To improve these debris models additional measurements are required. NASA has undertaken a measurement program that is designed to answer some of the questions about the environment, particularly in the low inclination low earth orbit region.

6.2.2 NASA MEASUREMENT PROGRAM

In order to better define the space debris environment NASA is utilizing radar, optical and space based systems to increase the accuracy of their models. Their main experiments are described below.

6.2.2.1 Radar Measurements

The primary objective of the NASA radar measurement efforts is to define the orbital debris environment. Other objectives include examining how the orbital debris environment changes over time and examining new sources of debris. The primary objective of defining the orbital debris environment will dictate how many of their experiments are conducted.

6.2.2.1.1 Multi-Wavelength Experiment

The objective of this program was to measure the radar cross section of the debris at multiple wavelengths and with optical telescopes simultaneously in order to determine an accurate correlation of the radar and the optical cross sections and how they correspond to actual physical size. This experiment utilized the four tracking radars at the Kwajalein Atoll Test Range and the Super-RADOT telescope. Calibration was provided by objects dropped by high altitude balloons that had been previously calibrated on a radar cross section static test range.[54] One hundred ten objects were successfully tracked by the ALCOR, MMW, ALTAIR, and TRADEX radars during mid-October 1990.[55]

6.2.2.1.2 Haystack Radar Debris Measurements

While many radar-based debris detection experiments are being proposed, the Haystack radar is the site of the main experiment now underway. The Haystack Long Range Imaging Radar is a high power X-Band (3 cm wavelength) radar operated by the Massachusetts Institute of Technology's Lincoln Laboratory. The data collection effort began in the summer of 1990 and over 1000 hours of data have already been collected. The Haystack orbital debris effort will collect 1200 hours of small debris measurements at up to 500 km altitude and 28 degrees orbital inclination. The radar is operated in the beam park mode which allows for constant volume searches, thus allowing for a simple geometry for flux calculations. Because the Haystack radar is located at

[54] Potter, Andrew (1991) NASA Radar Measurements of Orbital Debris, briefing at Phillips Laboratory, NASA, and Aerospace Orbital Debris Technical Interchange Meeting, 2-3 April 1991.

[55] Garcia, E., Pitts, C.,and Young, N. (1991) Orbital debris measurements using the Haystack and KREMS radars, Proceedings of the 1991 Space Surveillance Workshop, Lincoln Laboratory, 9-11 April 1991.

Millstone Hill in Massachusetts, in order to obtain measurements at 500 km altitude and 28 degrees orbital inclination the radar must be pointed down to just 10 degrees above the horizon. This increases the slant range to nearly 1700 km at 500 km altitude. Radar performance models have indicated that such a large number of 1-2 cm objects will not be detected at that range that the observations will not be adequate to specify the debris population, so plans are to increase the minimum detectable size at the expense of the limiting inclination.

The beam width of the Haystack radar is only 0.05 degrees, so objects pass through the beam in a few hundredths of a second. The narrow beam width is a result of the high gain antenna that Haystack utilizes which allows it to detect the smaller debris. The trade-off made for a high gain antenna with a very narrow beam width is that the search volume is small and the number of possible detections per hour is limited. These measurements will be used to determine statistically the debris environment for the Space Station; accurate determination of individual orbits is not possible from these measurements.

Early analysis of the data has indicated that the measured debris environment is close to the environment predicted by the NASA space debris models.

6.2.2.2 NASA Optical Measurements

NASA optical debris measurements have centered around three programs: the GEODSS Data provided by US Space Command, the Small Debris Telescope designed by NASA and the proposed Liquid Mercury Mirror Telescope.

6.2.2.2.1 GEODSS Data

The GEODSS program that utilizes data taken by US Space Command at Maui and Diego Garcia has been discussed earlier in Section 3. No additional measurements were conducted in 1991 for NASA. Analysis of the data shows that there were 2-3 times as many objects as those included in the Satellite Catalog.

6.2.2.2.2 CCD Debris Telescope

NASA has developed a small 32 centimeter telescope system specifically for orbital debris measurements. This system utilizes a time delay integration (TDI) mode that allows it to simulate a tracking telescope electronically. This is done by electronically shifting the accumulated signal across the detector as the same rate the object is moving across the detector. This results in large increases in sensitivity because the signal is integrated on only a few pixels and the integration time can be extended. The drawback of this method is that the rate of detection is significantly reduced because the instrument is only sensitive to objects traveling in a particular direction with the assumed velocity. The TDI method will be discussed in detail in Appendix A. NASA has begun making debris measurements with this system and results are not currently available.

6.2.2.2.3 Liquid Mercury Mirror

NASA has proposed a new liquid mercury mirror to make space debris measurements. This large 3-meter mirror would provide 7 square meters of collecting surface, which would increase its sensitivity to smaller debris.

NASA's Liquid Mercury Mirror telescope is a large system being designed around a relatively new concept to build large, inexpensive, fixed-direction telescopes. A large parabolic shaped dish is spun at a specific rate in order to maintain a thin film of mercury covering the surface. The mercury acts as the reflecting surface and provides an extremely smooth surface.

Since these mirrors are only applicable for vertical observations they have not been utilized by the astronomical community. Special precautions must be taken to ensure that vibrations and air currents are minimized to limit the effects of ripples and waves in the mercury. Development is underway and after design, test and checkout, possible sites include one near the equator, to allow for observations of debris in low inclinations.

Studies have indicated that large 10-meter mirrors are possible utilizing mercury. Initial analysis indicates that this may be an inexpensive method of increasing the collection area of optical measurements. A significant amount of work has been done on the liquid mercury mirrors at the University of Ontario where they plan on utilizing them for laser radar receivers for atmospheric measurements.[56]

6.2.2.3 Proposed Shuttle Experiments

In order to further characterize the space debris environment at the Space Station altitude, NASA has proposed the Debris Collision Warning Sensor Experiment. The Debris Collision Warning Sensor Experiment (DCWS) is a shuttle based experiment currently in the design stage. The primary objectives of DCWS are to search for objects greater than 1 mm near the Space Station's altitude as they cross the DCWS's field of view. The DCWS will also simulate an on-orbit collision sensor for the Space Station Freedom. Preliminary designs for the experiment include a 0.6 to 1 meter telescope with an advanced CCD detector system. Data will be stored on tapes for post flight analysis. DCWS will observe calibrated objects released from the shuttle bay during the mission. Other objectives of the experiment are to observe the geosynchronous ring and satellites passing near the Shuttle as computed from the Satellite Catalog.

6.3 Phillips Laboratory Space Debris Research Program

The Air Force's Phillips Laboratory has undertaken significant research on space debris. The peace-time program has two main thrusts. The first is the monitoring, modeling, and data management of debris information from low-Earth orbit. The second is discovering methods for

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[56] Lowe, R.P. and Turnbull, D.N., University of Western Ontario, London, Ontario, Canada, private communication.

debris minimization and spacecraft survivability. Both of these areas of research require identifying candidate technologies and setting milestones for accomplishing objectives. The research concerned with debris measurement and monitoring focuses on the 1 to 10 cm size range of space debris where data is very sparse.

War fighting and battle engagement issues are also being addressed by Phillips Laboratory (for example sensor discrimination capability in a debris environment generated by a kinetic energy weapon hit). Questions exist about what sensors will detect in a post attack environment and the effects of debris on damage/kill assessment. Any form of strategic defense system will require accurate damage assessment capabilities to determine if an additional weapon is required to kill the target. The effect of debris on decoys and re-entry vehicles are also undetermined.

In a post attack scenario, surviving re-entry vehicles must be discriminated against the background of debris in order to make an accurate damage assessment. Bulk filtering algorithms developed for this purpose are untested. Sensors must also be able to distinguish between deception techniques (such as decoy deployment) and actual debris in order to determine if the target has been destroyed.

Other war-time issues include the effect of either physical or operational degradation of space-based systems during battle. If a large amount of debris is created in a specific area, friendly systems may also be destroyed. Operational sensors may be overwhelmed with the number of objects and may affect other aspects of the battle. One must also consider the long term effects of any type of space-based battle on the near earth environment. Anti-satellite and anti-ballistic missile systems may need to be designed to minimize the debris they would create in order to prevent any long term detrimental effects on the near-Earth environment.

In order to address these issues, Phillips Laboratory has separated the peacetime and war fighting issues, allowing its different divisions to conduct research in their traditional areas of strength. The Geophysics Directorate, formerly the Air Force Geophysics Laboratory, is leading the peacetime environment, measurement and analysis effort along with the modeling and data management functions. The Geophysics Directorate has a long history of sensor and computer-based modelling programs.

The engagement issues are largely handled by the Weapons and Survivability Directorate at Kirtland Air Force Base, New Mexico which evolved from the old Air Force Weapons Laboratory. This group is analyzing aspects such as spacecraft survivability, debris discrimination and debris processing. This group also works with the Defense Nuclear Agency in the area of breakup modelling.

6.3.1 PHILLIPS LABORATORY'S OPTICAL MEASUREMENT PROGRAM

The Phillips Laboratory has established an overall program to characterize the orbital debris environment by using optical systems. This effort includes a number of sensors, each with different capabilities and characteristics. The participating/competing sensors systems, shown in Figure 53, are:

• The Geophysics Directorate's Wright Patterson AFB 100" Collimator
• The Advanced Maui Optical Site (AMOS)
• The Malabar Test Range System in Florida
• The Starfire Optical Range (SOR)
• The Lincoln Laboratory Experimental Test Site (ETS)

Other sites participating in this cooperative effort with Phillips Laboratory and NASA are the Haystack radar system at Millstone Hill in Massachusetts and the Liquid Mercury Mirror (LMM) being designed by NASA.

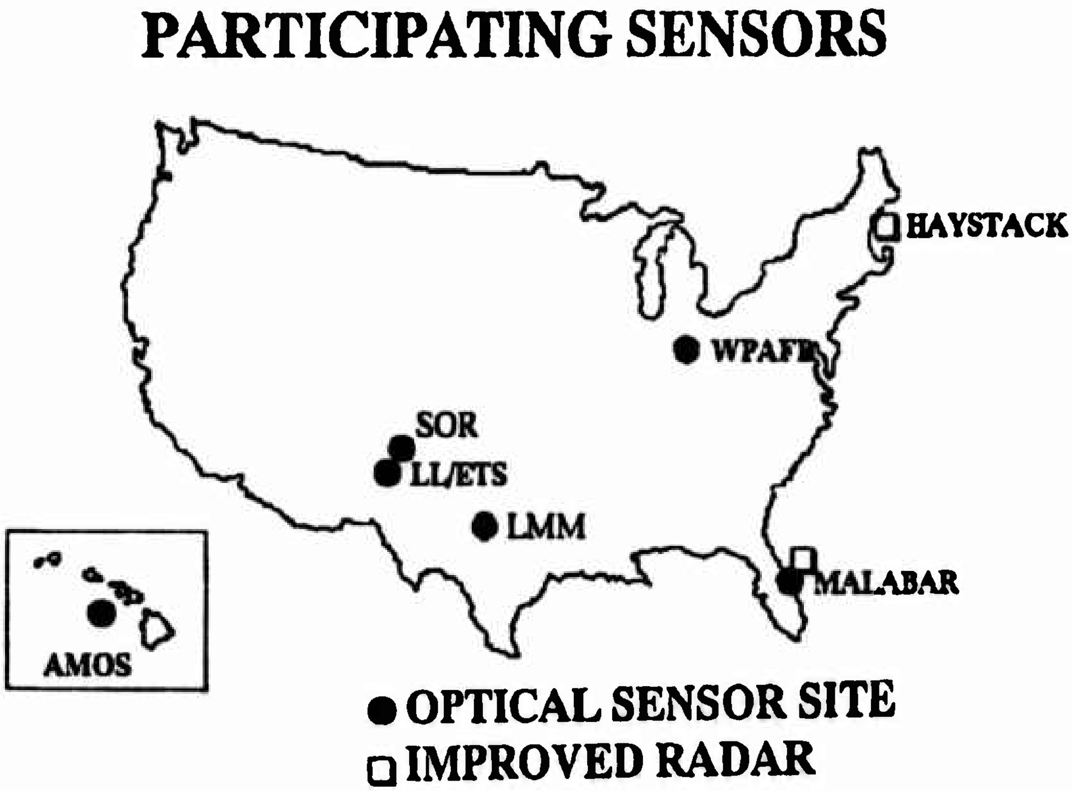

Figure 53. Participating Sensors

The Wright Patterson 100 inch collimator facility was originally built to produce andtest optical components for high altitude photographic systems and satellites. This facility has a 12 story vacuum chamber that houses the collimator. At the lowest level of the facility there is a very high quality, 2.54 meter (100-inch) mirror with a 15.24 meter (600 inch) focal length. The collimator facility was moth-balled shortly after it was built since more modern techniques had been developed. In 1988, the system was restored and used for high altitude laser radar studies of the upper atmosphere by the Geophysics Laboratory (now the Geophysics Directorate of the Phillips Laboratory). This system is designed to provide a database of the smaller objects to evaluate debris models at the smaller end of the spectrum of detectable objects.

The Advanced Maui Optical Site (AMOS) was originally designed to obtain high accuracy photometric data and imaging data on satellite systems. This site is co-located with one of the GEODSS sites at the top of Mt. Haleakala, on the island of Maui. AMOS maintains a number of telescope systems with varying diameters and fields of view.

The Experimental Test Site (ETS) operated by Lincoln Laboratories in Soccoro, New Mexico was the original development site for the GEODSS system. ETS has two 60 inch telescope systems located 60 meters apart. This unique feature allows for a parallax measurement to discriminate against micro meteor trails as they enter the earth atmosphere.

The Star Fire Optical Range outside Albuquerque, New Mexico is part of the Phillips Laboratory's atmospheric compensation effort. This system currently consists of a 1.5 meter telescope. Future construction will provide a 3.5 meter telescope. Current results of research there have been recently unclassified and have indicated that the image compensation techniques used have allowed for better image quality than those used in the Hubble Space Telescope.[49]

The Malabar Test Range has a unique set of sensors and telescopes that support various Air Force requirements. It has both a visible and a long wavelength infrared capability. This system provides advanced imaging of satellite systems for the Air Force. It is located at Palm Bay, Florida.

The main parameters of the capabilities of various sites are the size of the telescope, the field of view of the telescope, and the darkness of the sky. Other considerations include the ability of the telescope to scan and the latitude of the site. A summary of the most important information concerning orbital debris measurements for the primary sites discussed here is shown in Table 16. The NASA liquid mercury mirror was not included due to a lack of data at this stage of the design effort. ("Sky" in Table 16 refers to the night sky background in optical magnitude.)

Table 16. Optical Site Characteristics

Optical Site Characteristics

Site	LAT (deg)	SKY (mag)	Diameter (m)	FOV (deg)	SCAN
AMOS	20.7	22.2	0.56	0.5	Y
ETS	33.8	22.2	0.79	1/0.5	Y
GP/WP	39.0	21.0	2.54	0.2	N
MALABAR	28.2	20.4	0.85	0.5	Y
	28.2	20.4	0.69	3.5	Y
SOR	35.0	19.7	1.5	0.72	Y

To illustrate the efforts required to make optical observations, Appendix A provides significant details of the Phillips Laboratory optical measurement program at Wright Patterson Air Force Base, Ohio. It describes in detail the various methods for making measurements and the tradeoffs associated with each. Appendix A also provides very detailed calculations as to the minimum detectable size for all the Phillips Laboratory optical measurement sites.

6.3.2 OTHER SOURCES OF RADAR DATA

Other measurements data Phillips Laboratory is evaluating for debris measurements include radar data at a number of scientific radar sites. One example is the incoherent scatter radar site at Sondrestrom, Greenland. This radar is run by SRI International for the National Science Foundation. Its primary mission is to study the ionosphere in the auroral oval. However, it also detects space objects approximately 2-3 times an hour. Due to its large size, high power and extremely sensitive receivers it should be able to see objects as small as 3 cm. Years of data are stored on magnetic tape, but the site recently switched to optical discs. Over 1200 hours of radar data are currently available through NSF and SRI.

6.4 Conclusions on Space Debris Research Efforts and Measurements

As shown, each organization has undertaken a research effort aimed at solving its particular problems. While there are some overlaps between programs, they are minor. Coordination and cooperation are one of the highlights of the effort. Several technical interchange meetings have been conducted at Phillips Laboratory and US Space Command. Many measurements are needed to adequately define all aspects of the space debris environment. These measurement program will provide a significant amount of data and will help define the extent of the space debris problem.

7. SPACE DEBRIS EFFECTS MITIGATION

There are many ways to minimize the dangers of collisions with orbital space debris. They include debris reduction strategies, shielding, on-orbit maneuvering, and robust space architectures. Each of these mitigation efforts represents a different approach and method of obtaining the same objective: ensuring that the use of space for commercial, scientific and military purposes can be pursued safely and reliably.

7.1 Collision Avoidance of Space Debris

Avoiding collisions with resident space objects would be a very difficult task without the information provided by the US Space Command and its Space Surveillance Network. The catalog that US Space Command maintains currently consists of 7,000 objects and is increasing at an average annual rate of 6-7 percent per year.

Potential collisions between critical space systems, such as the shuttle, and known space objects can be avoided by suitable orbital maneuvers. To date this is the only active debris avoidance method employed by the United States. As discussed in earlier sections, it is possible to predict the orbits of known debris and spacecraft to determine the possibility of a collision. But this is practiced only for high value systems such as the Space Shuttle, certain military satellites, and the future Space Station because of limitations in computer resources and in the accuracy of the predictions and measurements.

The standard accuracy with which Space Command determines an orbit is a few kilometers within a few days of the observation time.[57] Ground-based measurements are limited in their accuracy because the type of radars used are not meant for metric accuracy, and inherent errors in the measurements due to the effects of the ionosphere on signal propagation exacerbate this limitation. If predicted orbits are limited to errors of only 3 km of the actual orbit, then a 10 square meter satellite could receive 2,800,000 collision warnings for each actual collision.[58] The accuracy of the predicted orbits at low altitudes degrades quickly because of the limitations in predicting the effects of the atmosphere with existing models.

Another limitation in orbital prediction is that the Space Surveillance Center and the Alternate Space Surveillance Center use general perturbations, an analytical theory, instead of special perturbations, or numerical integration. General perturbation theory, as used at the Space Surveillance Center, is less accurate than the modern special perturbation theory methods used for accurate orbit prediction. This decision is determined by the available computer resources because special perturbation theories require significantly more computer calculations per

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[57] Knowles, Stephen H. (1990) Orbital elements determination for breakups and debris, AIAA 90-1348 from the AIAA/NASA/DOD Orbital Debris Conference: Technical Issues & Future Directions, 16-19 April 1990, Baltimore, Maryland.

[58] Based on the area of a circle with a 3 km radius (2.8×10^7 m^2) and the 10 m^2 area of the satellite.

satellite. The general perturbation theory, as implemented at Space Surveillance Center, is presently limited to accuracies of approximately 300 meters.[57] More accurate orbits are possible provided warning time is sufficient to direct additional radars designed to provide more accurate velocity and position measurements and translate the data into new orbital parameters. Use of special tracking radars can produce orbital parameters and measurements to provide orbit predictions to accuracies of a few meters as is done with the Global Positioning Satellites.

Debris avoidance maneuvers can be accomplished with small maneuvering jets provided that adequate warning time is available. Small velocity changes can provide significant changes in positions within an orbit. Debris avoidance maneuvers would not necessarily waste fuel. Satellites that require periodic re-boost could plan debris avoidance maneuvers into their orbit-raising firings that need to be performed in any event. Engine firings could be planned into orbit raising maneuvers for the Space Station and other systems. This type of unscheduled engine firings may cause significant problems with scientific missions on-board the Space Station, especially for long term zero gravity experiments.

7.1.1 ON-ORBIT WARNING

Space-based procedures to avoid collisions between objects is currently not a viable alternative. Any warning system that could detect objects on a collision course with another space object would provide too short a warning prior to impact. Considering that closure velocities are on the order of 10 km/sec, a maneuvering rocket system that could provide sufficient acceleration to avoid collision on short notice would dominate the spacecraft design.

Yet the idea of space-borne warning sensors and quick reaction rockets for protection has been advanced by some people. This approach requires a method of detecting debris, either radar or optical, that can see potential threatening debris far enough away to maneuver the satellite to avoid collision. The sensor system would have to accomplish a search pattern covering the many directions from which debris may approach in both sun illuminated and eclipsed conditions. After an initial detection the sensor system would have to discriminate between near approaches and collisions, determine a method for maneuver and execute a rocket firing in a very short period of time. This may require autonomous control by the satellite because the reaction time would be very short.

Since closing rates between objects can be as high as 14 kilometers per second at low-Earth orbit, if a small space-based sensor system could reliably detect debris on the size of 1 cm at 140 km, it would provide only 10 seconds warning before a collision. Within the 10 seconds from first detection the sensor must confirm a collision course with a certain level of confidence, decide that the satellite is capable of maneuvering despite mission requirements and maneuver the satellite to a safe distance from the debris path. This safe distance is a function of the accuracy with which the debris path can be determined.

If it took 5 seconds to determine the course of the debris to the necessary accuracy and if a minimum of 10 meters separation with the debris were required, significant propulsion systems would be needed. A satellite that must maneuver 10 meters in 5 seconds would require an acceleration rate of approximately 1 meter per second squared. For a 2500 kilogram satellite this requires a 2.5 kilonewton rocket, which is equivalent to the Orbital Maneuvering Engine on the Space Shuttle (2,727 newtons) and significantly larger than any system used for station keeping (1 newton). If a decision could be made with 10 seconds remaining until impact, the satellite would require a 500 newton engine, which is nearly twice as large as the shuttle's primary reaction control system.

To utilize such a maneuvering system satellites would require very significant redesign to withstand rapid accelerations while solar panels, booms and antennas deployed. This would result in significant additional weight and cost. The sensor and engine would have to be made extremely reliable because any failure may result in its removal from a useful orbit or a waste of fuel. A major consideration is that maneuvering systems' failures may cause more satellite losses than potential losses due to debris. The extra engines and propellent also raise the risk of additional on-orbit propulsion related explosions and hence additional debris. In any case such a maneuvering system would dominate most spacecraft and would not be practical because of the cost of development and the risks of failure involved. Because of these problems this approach is not promising.

7.2 Passive Protection

Another method for protection against collisions with space debris involves hardening satellites and space systems to survive collisions. Another is to design systems that can lose a single satellite and still meet its requirements.

7.2.1 SPACE DEBRIS SHIELDS

The response to the threat of space debris NASA has chosen for the Space Station is to use shields to protect the Space Station against possible debris impacts. These shields are typically light layers of material that cause the debris to fragment and vaporize. Shields will be used to protect the critical portions of the Space Station, such as the manned modules and fuel tanks. Because of the additional weight required, other systems such as solar arrays, antennas, and radiators cannot be shielded. But protecting critical components with shields adds significantly to the cost and weight of the Space Station.

The amount of weight and cost depends largely on the amount of risk one is willing to take. A space system is much more likely to be hit by a millimeter sized object than by a 5 cm sized object. By shielding against a 1 millimeter sized object you reduce your risk to those objects but not the risk due to larger objects. Table 17 shows the shield mass per unit area required to shield against various size debris. Associated with the weight is the implicit cost of launching the shields.

Table 17. Shield Mass Per Unit Area[4G]

SHIELD MASS PER UNIT AREA (No perforation of rear wall)
• 3.2 mm Aluminum Projectile (45 mg), Normal Impact, 6.5 km/sec
-- Monolithic Aluminum Plate: 3.53 g/cm^2.
• 3.2 mm Aluminum Projectile (45 mg), Normal Impact, 10 cm Spacing
-- Whipple Shield: 0.60 gm/cm^2.
-- Nextel MS Shield: 0.29 g/cm^2.
-- Mesh Double-Bumper: 0.26 g/cm^2.
• 3.2 mm Aluminum Projectile (45 mg), 45 deg Impact, 10 cm Spacing
-- Whipple Shield: 1.22 g/cm^2.
-- Nextel MS Shield: 0.31 g/cm^2
-- Mesh Double-Bumper: 0.36 g/cm^2.
• 3.2 mm Aluminum Projectile (45 mg), Normal Impact, 5 cm Spacing
-- Whipple Shield: 0.80 g/cm^2.
-- Nextel MS Shield: 0.52 g/cm^2
-- Mesh Double-Bumper: 0.42 g/cm^2.
• 9.5 mm Aluminum Projectile (1.3 g), Normal Impact, 30 cm Spacing
-- Whipple Shield: 1.35 g/cm^2.
-- Nextel MS Shield: 0.97 g/cm^2
-- Mesh Double-Bumper: 1.08 g/cm^2.
• 6.4 mm Aluminum Projectile (0.37 g), Normal Impact, 20 cm Spacing
-- Whipple Shield: 0.96 g/cm^2.
-- Mesh Double-Bumper: 0.64 g/cm^2.

7.2.2 WHIPPLE SHIELD

The idea of a shield is to spread the energy of a collision over a large area instead of a small point. This can be done by placing a thin shield or bumper in front of a spacecraft's surface. The purpose of this shield is not to stop an object from passing though, but to break it into smaller fragments and gasses that will spread over a larger area before reaching the spacecraft's bulkhead. When a high speed object collides with the bumper, it fragments and/or vaporizes depending on the velocity of collision and the material of the projectile. The resulting particles spread before hitting the next layer of the shield of bulkhead. A single bumper system is commonly known as a Whipple shield and was first considered during the Apollo missions. Many modifications and adaptations on this concept have evolved for possible use on the Space Station. The Whipple shield is heavy compared to other shielding concepts.

The Whipple shield is included in the initial design of the bulkhead of the Space Station. This would consist of one or two layers of aluminium plates spaced a few inches apart covering the exposed portions of the inhabited modules. This would provide some protection against debris. Figure 54 shows the ballistic limit curve (the diameters and velocities that will cause failure by detached spalling or perforation to the rear bulkhead) for the Whipple shield. The shape of the curves denotes the different velocity regimes for the projectiles discussed in Section 4.

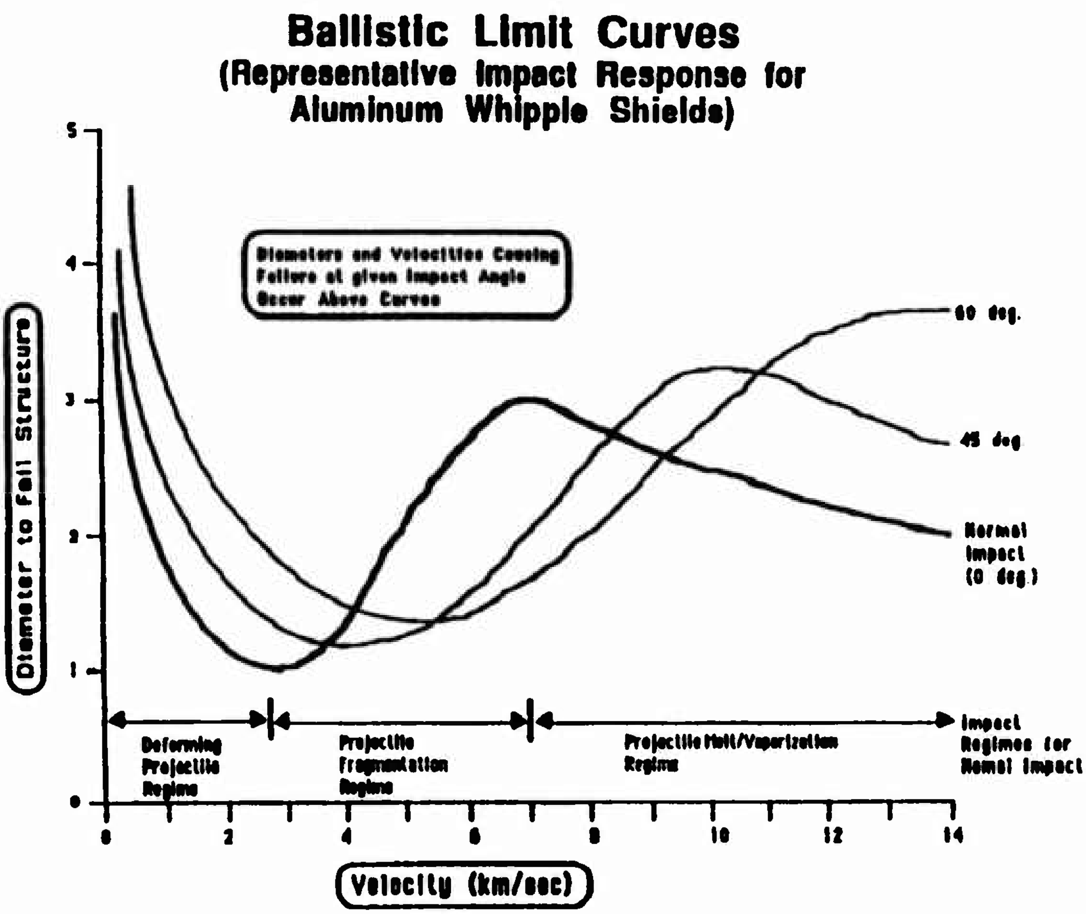

Figure 54. Ballistic Limit Curves for the Space Station protected by Aluminum Whipple Shields. "Diameter to Fail Structure" is the diameter in centimeters at a velocity that is assumed would cause the failure of the Space Station structure[40]

Several other types of shields have been studied and considered for possible use with the Space Station. These shields include mesh double-bumper shields and multiple fabric shields. With each of these systems come significant weight and cost penalties. These systems also provide only a limited amount of protection against small objects. It is not considered practical to shield against objects much larger than 1 cm.

7.2.3 MESH DOUBLE-BUMPER SHIELD

The mesh double-bumper shield is a modification of the Whipple shield. It consists of two Whipple shields stacked together, utilizing an aluminum mesh to reduce the weight compared to the solid aluminum bumper. Figure 55 shows the proposed configuration.

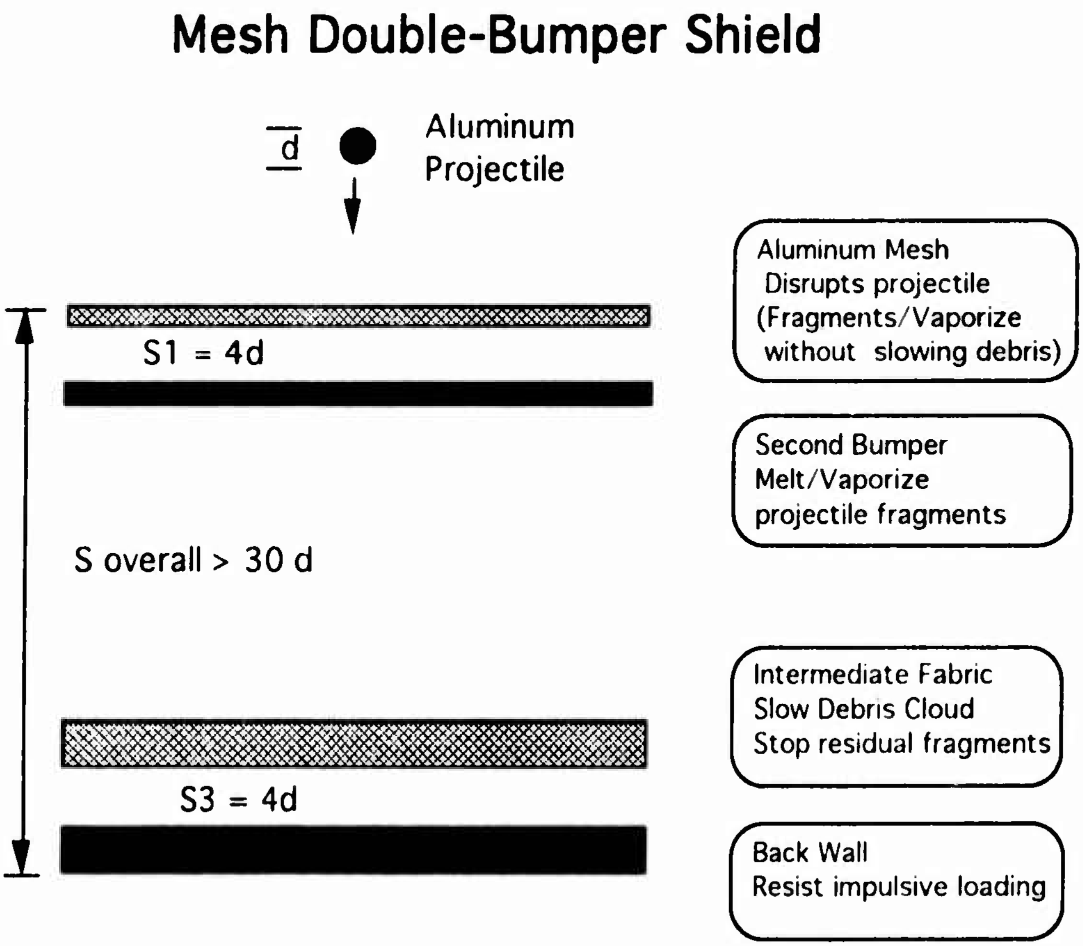

Figure 55. Mesh Double Bumper[40]

Collisions with mesh also result in a greater spread of the debris clouds formed after collisions.[40] This allows for greater protection with closer spacing between bumpers. The second bumper is used to deliver a second shock to remaining large fragments. An intermediate layer of high strength fabric (either kevlar or a ceramic fabric known as Nextel) is used to slow the debris cloud and decrease the impulsive load on the bulkhead.

While this shield concept has undergone significant testing, additional development work on it is still required. Alternative materials such as steel fabrics must be analyzed and ballistic limit tests must be conducted before the design of flight hardware can begin.

7.2.4 MULTIPLE SHOCK SHIELD

The multiple shock shield uses many fabric shields successively to break up the high velocity debris before it impacts the bulkhead. Multiple ultra thin sheets reduce the weight of the shield. The successive shocks from the shields raise the temperature of the projectile, causing it to vaporize or fragment. These sheets can be made from flexible or rigid materials. One of the materials that NASA is considering includes Nextel. This fabric is versatile and provides many on-orbit shielding options. There is still a considerable amount of work to be done on optimizing shield materials, reducing their weight, and assessing alternative shielding options. The multi-shock shield is shown in Figure 56.

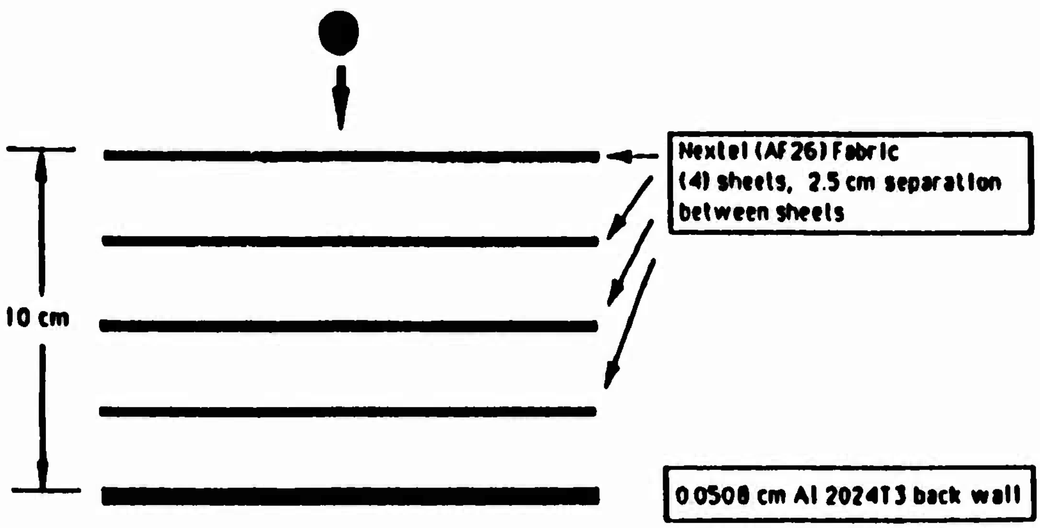

Figure 56. Geometry for a Multiple Shock Shield [40]

Figure 57 shows the diameter limit for a multiple shock shield against aluminum debris at various angles for no penetration or internal spalling of the bulkhead. The maximum sustainable diameter for this design as shown is on the order of 0.1 - 0.3 cm.

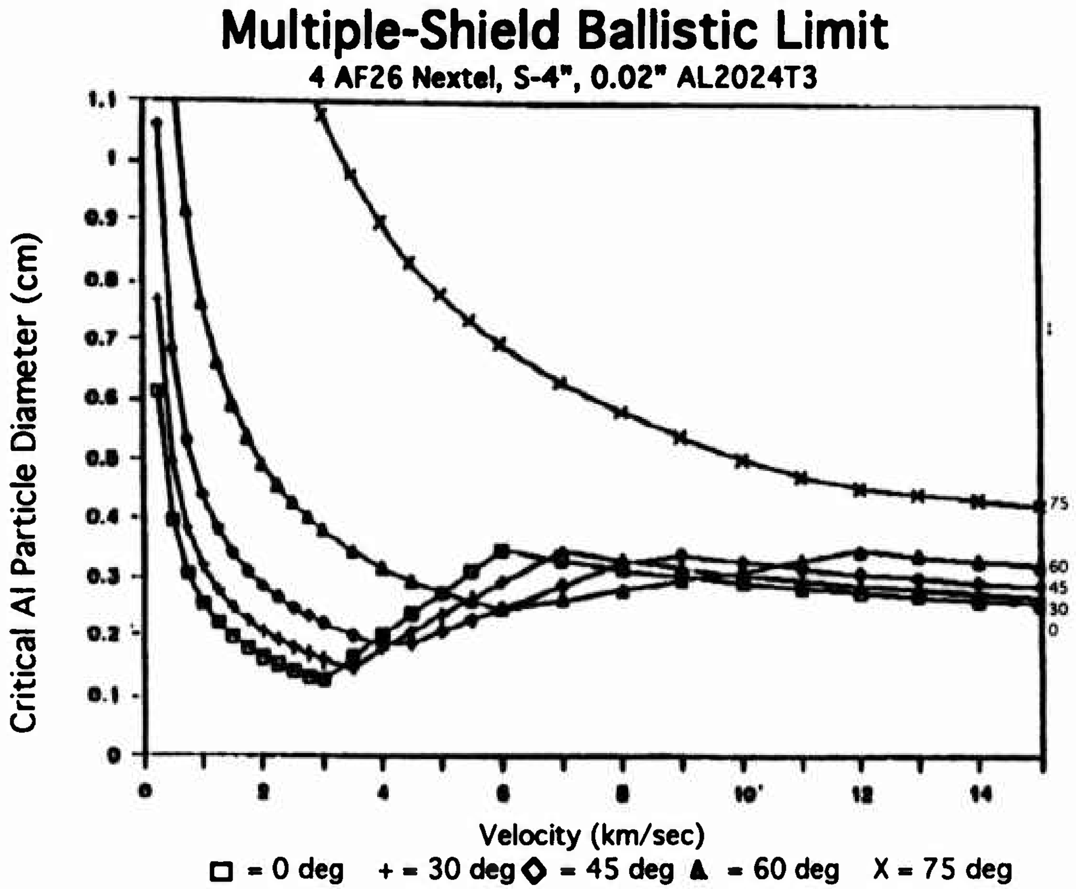

Figure 57. Multi-shock Shield Ballistic Limit[40]

Shield deployment mechanisms range from deployable booms pulling sheets of fabric from window blind type rolls, to advanced air bag deployment technology. Significant design and cost analysis must be done before any shielding program is undertaken. The deployable shield concept based on rolling out fabric similar to a window blind is shown in Figure 58. These shields would be placed around critical areas of the Space Station to provide additional protection against debris.

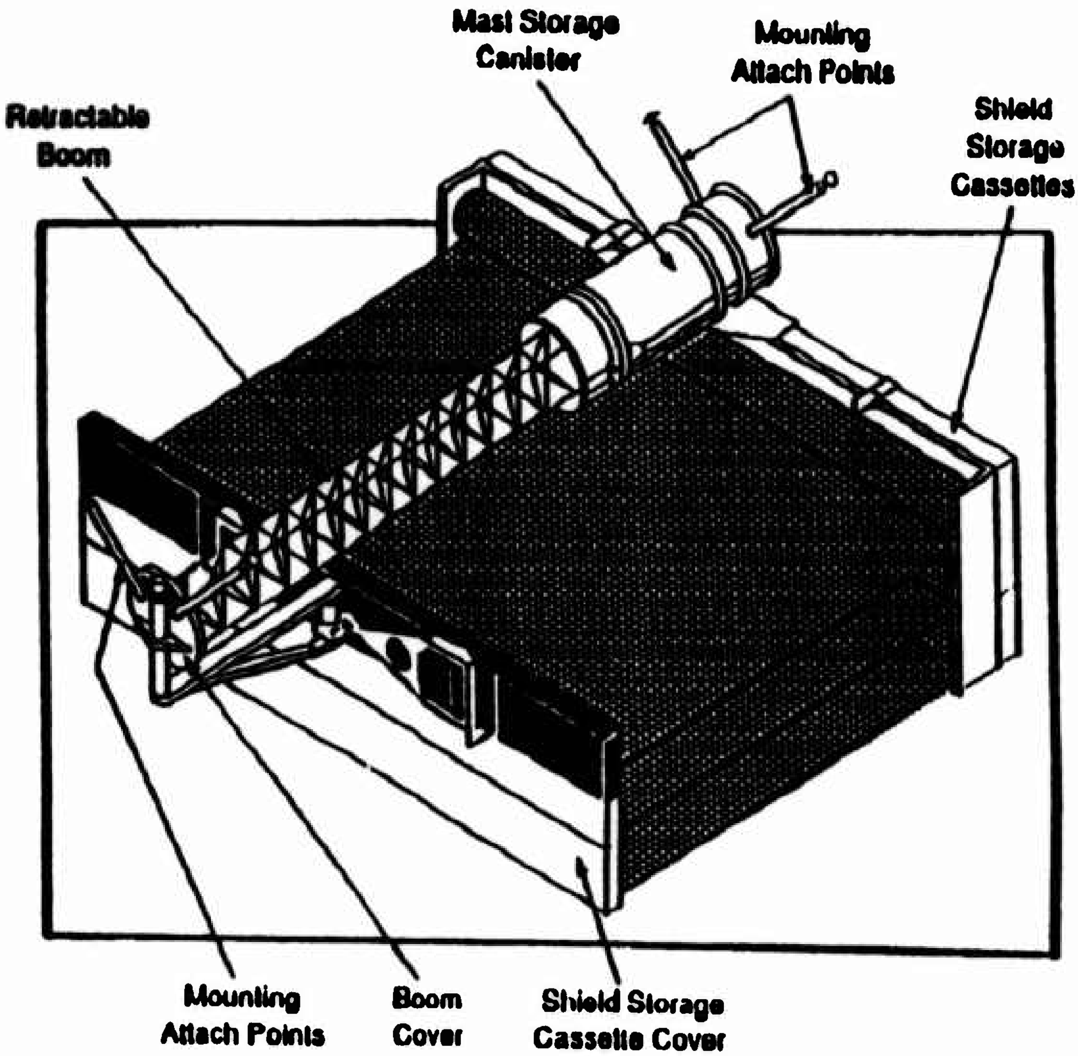

Figure 58. One Proposed Space Station Freedom Shield Deployment Mechanism[40]

None of these systems as designed for the Space Station are capable of or envisioned to protect against larger, though still untrackable debris, in the 3 - 10 cm range. Shielding against these larger objects is impractical due to the cost and the weight involved. If the risk is higher than acceptable limits, other means of protection are required.

7.3 Robust Systems

Satellites are launched into orbit to accomplish a mission, civilian or military. A method to ensure that loss of a single satellite does not cripple the mission the satellite was meant to carry out is to provide redundancy. An example of such built-in redundancy is the Global Positioning

System. The failure of a single satellite of the system will not cause significant loss of mission capability since the system consists of a constellation of 18 - 24 satellites. Such redundant systems "fail gracefully" as satellites are taken out of action. For military missions in space this has been a major consideration since the development of the Soviet anti-satellite system. Many military space systems such as GPS and AFSATCOM were designed to continue functioning even after the loss of several satellites.

Another approach is to orbit additional sensors performing a given mission on different satellites to provide a backup system in the event that a primary mission satellite fails or collides with debris. An example of this approach is the nuclear burst detection system that is mounted on the GPS satellites. This use of redundant systems removes most of the immediate threat of space debris because even if a satellite is destroyed by debris then the mission can still be accomplished.

A study titled the "Assured Mission Support Space Architecture" was performed by United States Space Command.[59] Although aimed at a wartime scenario, the study explores ways to assure space-based mission support to military units. Many of the considerations for robust mission capabilities during wartime would mitigate the possible effects of space debris.

However, the United States is reported to have several systems that do not meet the criteria of robust space systems. In the 1980's it was reported that the United States had a single optical surveillance system in orbit. This single system put the surveillance capabilities of the United States at risk to space debris. If the reconnaissance satellite was hit by debris, the results would be nearly indistinguishable from an anti-satellite weapons attack from a direct ascent or an undetected Soviet ASAT weapon. If such an event occurred during a time of heightened alert or tension between the US and USSR, the resulting overreaction could prove disastrous.

It will not always be possible to deploy a robust system. The Space Station Freedom and the Space Shuttle are examples of non-robust systems. They do not fail gracefully, as shown by the Space Shuttle Challenger disaster that grounded the shuttle fleet for two and a half years. The reliance on a single large space station is another example of a non-robust system. If for some reason the Space Station were put out of commission, all its missions would collapse.

Mitigating the effects of collisions by avoidance of debris will have only a limited effect. Space Command can provide warning of a possible close approach with tracked debris to some high value systems. This only provides collision warnings for about 10 percent of the dangerous debris. Collision warnings from Space Command are not a practical solution for most satellite systems because of the number of warnings per actual collision is very high due to uncertainties in the orbit determination and prediction for objects in space. On-orbit warnings are not practical because of the short warning time available for collision avoidance maneuvers. The weight and cost of such a propulsion system would dominate the spacecraft.

[59] United States Space Command, *Assured Mission Support Space Architecture*, Peterson Air Force Base, Colorado.

Passive protection systems using shields are heavy and expensive and provide only a limited amount of protection. Shields designed to protect against debris larger than a few centimeters are not practical. Robust space systems provide protection of the mission against space debris by insuring system operation despite the loss of a single satellite.

8. LEGAL ASPECTS OF SPACE DEBRIS

There are two main bodies of law and regulations that can apply to space debris: international treaties and domestic laws and regulations. Neither of these as presently written or interpreted address directly the growing problems associated with space debris. Regulatory agencies on both the national and international level form a patchwork of organizations covering various aspects of space activity. Treaties covering aspects of debris are vague and open to interpretation. At present, national laws are mostly silent on the problem of debris -- they merely require that activities conform to all international treaties and national interests of the United States.

8.1 International Treaties

The major international organization that has been involved with the development of international space law is the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS). This committee was formed in 1958 to report on potential conflicts in international law and policy. It identified three primary problems that the United Nations needed to address: free access to outer space, liability for damages, and allocation of the radio spectrum for objects in orbit.

By 1975, UNCOPUOS negotiated four international treaties associated with space that form the backbone of international space law: the Outer Space Treaty (1967), the Agreement on the Rescue and Return of Astronauts (1968), the Convention on International Liability (1972), and the Convention on Registration of Objects (1975). These treaties cover numerous areas, including the peaceful use of space and the possible contamination of Earth from space-borne diseases. These four treaties form the basis for the current international space law.

At the time these treaties were negotiated there were only two space-faring nations, the US and the USSR. Since then the major conflicts have been not between the US and USSR, but between these two nations and non-space-faring nations.[30] Agreement on these treaties was by consensus when no country was opposed to a provision.

Since 1975, the committee has negotiated only one treaty. This fifth treaty, the Treaty Governing the Activities on the Moon and Other Celestial Bodies (1979) (otherwise known as the Moon Treaty), was negotiated and signed, but it has been ratified by only seven nations. Neither

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[30] Goldman, Nathan (1988) *American Space Law*, Ames Iowa: Iowa State University Press, p. 29.

the United States, the Soviet Union, nor any other major space power, has ratified the Moon Treaty.

Other areas of international legal concern with space activities have been the demilitarization of space, solar power satellite systems, direct broadcast satellites and the definition of outer space. The major conflicts are once again between space-faring and non-space-faring nations.

The remaining part of this section discusses each of these five treaties and their possible application to the problems of space debris.

8.1.1 THE OUTER SPACE TREATY

"The Treaty on Principles Governing the Activities of States in the Exploration and Uses of Outer Space, Including the Moon and Other Celestial Bodies" or the "Outer Space Treaty" was ratified in October of 1967 and signed by almost 100 nations. It is the broadest of all treaties dealing with outer space and is the one that comes closest to addressing the problems of space debris. The Treaty has seventeen articles which address issues such as the rights and duties of space-faring nations, military activities in space, the status of astronauts, and environmental protection.

The first article outlines the general principles of use of outer space.

Article I

> The exploration and use of outer space, including the moon and other celestial bodies, *shall be carried out for the benefit and in the interest of all countries*, irrespective of their degree of economic or scientific development, and shall be the providence of all mankind.
>
> Outer space, including the Moon and other celestial bodies, *shall be free for the exploration and use by all States without discrimination of any kind*, on the basis of equality and in accordance with international law, and there shall be free access to all areas of celestial bodies.
>
> *There shall be freedom of scientific investigation in outer space*, including the Moon and other celestial bodies, and States shall facilitate and encourage international co-operation in such investigations.

It could be argued that the creation of space debris runs counter to the language "for the benefit and in the interest of all countries". While it is true space debris does not benefit countries, the primary mission of space operations usually does. Space missions are performed to aid people on Earth through providing communication, experiments, imaging, not to pollute outer space. In any case the language is too vague to be applied to specific problems with space debris.

Article I continues by making it clear that all nations can use and explore space on the basis of equality without interference. Nations with developing space programs may argue that they should be allowed to produce the same amount of debris that the advanced space powers did as they developed their space programs. Anything else, they would argue, is discrimination against those who entered space at a later date and is not allowed under Article I.

The last sentence of Article I further erodes its use as a basis for space debris mitigation. "There shall be freedom of scientific investigation in outer space" indicates that countries are allowed to undertake scientific investigations without interference from others. Strict debris mitigation practices could limit the experiments a country is allowed to conduct which would limit the freedom of scientific investigation.

Article III of the treaty limits a nation's right to explore space to activities that conform to international law and are in the interest of international peace and security.

Article III

> States Parties to the Treaty *shall carry on activities in the exploration and use of outer space*, including the moon and other celestial bodies, in accordance with international law, including the Charter of the United Nations, *in the interest of maintaining international peace and security and promoting international cooperation and understanding.*

While it could be argued that creation of space debris does not help maintain international peace and security, this is a weak argument and could not be a basis for space debris mitigation regulations. The Treaty was concerned with payloads launched into orbit and not debris. It is difficult to define the creation of a small amount of debris from a single launch as a threat to international peace and security.

Article V covers the status of astronauts.

Article V (third sentence only)

> States Parties to the Treaty shall immediately inform the other States Parties to the Treaty or the Secretary-General of the United Nations of any phenomena they discover in outer space, including the moon and other celestial bodies, which could constitute a danger to the life or health of astronauts.

The first two sentences cover the duties of nations to aid astronauts in distress. The last sentence of this article creates the duty to inform another nation of any phenomena that could constitute a danger to life or health of astronauts. Since collision with space debris could be considered an event threatening the life of an astronaut, this could be used to require nations with space surveillance equipment to warn other countries of potential collisions between space objects, as the US already does for its manned space flights. This could also require the United States and other countries to provide information about the extent of the space debris problem to the United Nations.

Article VI holds nations responsible for the actions of any of their citizens or corporations in outer space.

Article VI

> *State Parties to the Treaty shall bear international responsibility for national activities in outer space,* including the moon and other celestial bodies, *whether such activities are carried on by government agencies or by non-governmental entities, and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty. The activities of non-governmental entities in outer space, including the Moon and other celestial bodies, shall require authorization and continuing supervision by the appropriate State Party to the Treaty.* When activities are carried on in outer space, including the moon and other celestial bodies, by an international organization, responsibility for compliance with this Treaty shall be borne both by the international organization and by the State Parties to the Treaty participating in such organization.

This article makes the state the responsible party for monitoring the activities of its citizens to ensure they comply with international law. This provides clear authority to the governments to control the space activities of its nationals in as far as international law can authorize governments to take actions on a national level. This authority would aid the enforcement of any space debris policies that were drawn from the treaty by holding the nations accountable.

Article VII simply extends potential liability to countries buy'ng space systems or launches from other countries.

Article VII

> Each State Party to the Treaty that launches or procures the launching of an object into outer space, including the moon and on the celestial bodies, and each State Party from whose territory or facility an object is launched, is internationally liable for damage to another State Party to the Treaty or to its natural or juridical persons by such object or its component parts on the Earth, in the air space or in outer space, including the moon and other celestial bodies.

This in effect widens the responsibilities and liabilities to include non-space-faring nations who procure space systems from other countries. This eliminates some potential problems of countries using a flag of convenience country to avoid liability and potential debris mitigation programs.

Article VIII covers ownership of objects in space. It states explicitly that ownership, jurisdiction and control over an object launched into space is not effected by its presence in space.

Article VIII

> A State Party to the Treaty on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object, and over any personnel thereof, while in outer space or on a celestial body. Ownership of objects launched into outer space, including objects landed or constructed on a celestial body, and their component parts, is not affected by their presence in outer space or on a celestial body or by their return to Earth. Such objects or component parts found beyond the limits of the State Party to the Treaty on whose registry they are carried shall be returned to that State Party, which shall upon request, furnish identifying data prior to their return.

This was really meant to prevent nations from acquiring other countries' property, but it could be used to keep a nation from disassociating itself from debris and the potential liability associated with it.

Article IX is designed to protect the environment and comes the closest to addressing the problems of space debris. It deals with environmental protection of earth, outer space and other celestial bodies.

Article IX

> *In the exploration and use of outer space, including the moon and other celestial bodies, States Parties to the Treaty shall be guided by the principle of co-operation and mutual assistance and shall conduct all their activities in outer space, including the moon and other celestial bodies, with due regard to the corresponding interests of all other States Parties to the Treaty.* State Parties to the Treaty shall pursue studies of outer space, including the moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter, and where necessary, shall adopt appropriate measures for this purpose. *If a State Party to the Treaty has reason to believe that an activity or experiment planned by it or its nationals in outer space, including the moon and other celestial bodies, would cause potentially harmful interference with activities of other State Parties in the peaceful exploration and use of outer space, including the moon and other celestial bodies, it shall undertake appropriate international consultations before proceeding with any such activity or experiment.* A State Party to the Treaty which has reason to believe that an activity or experiment planned by another State Party in outer space, including the moon and other celestial bodies, *would cause potentially harmful interference with activities in the peaceful exploration and use of outer space, including the Moon and other celestial bodies, may request consultation concerning the activity or experiment.*

Article IX states that in the exploration and use of outer space, states should be guided by the principle of cooperation and mutual assistance and that they should conduct their activities with due regard to the corresponding interests of all other nations. It goes on to say that nations shall pursue studies of outer space and celestial bodies and conduct explorations of them so as to avoid their harmful contamination, and where necessary adopt appropriate measures for this purpose. This could be construed as applying to space debris; however, the main concern at the time of passage was the introduction of extraterrestrial diseases into the Earth's environment. The secondary concern was to protect the Moon and other planets from pollution that would negate future experiments.

There was significant discussion during the negotiation of the Treaty regarding the extent and meaning of Article IX. Earlier proposals had general terms relating to the protection of the space environment such as the requirement not to allow measures that "might in any way hinder the exploration or use of outer space for peaceful purposes by other countries...."[11] The earlier proposed language was linked to a provision allowing the exploration activities of outer space only after prior discussions and agreement was reached between all parties concerned. This language was dropped and does not appear in the final treaty which indicates that a more narrow interpretation is appropriate.

Since this treaty is binding on the nations as they interpreted it at the time of passage, it is important to look at statements made by the United States at that time. The US Ambassador Arthur Goldberg stated that Article IX "includes a specific obligation to avoid harmful contamination of outer space or of celestial bodies and also to avoid adverse changes in the terrestrial environment."[11] It is unclear if his reference to contamination would include debris. To date it has not created an obligation on the part of the United States to mitigate the amount of debris that we produce. If this section were re-interpreted to clearly apply to space debris, it would provide an easy way to create an international obligation to control the increase of space debris. This could then be used to allow US laws, which will be discussed latter, to clearly apply to debris mitigation.

In the Outer Space Treaty there are no direct provisions for international regulation to limit the development of space debris. While some articles could possibly be interpreted to apply to space debris, (such as the ones dealing with harmful contamination and interfering with other nations rights to explore and use space), in fact they do not apply as presently interpreted.

8.1.2 AGREEMENT ON THE RESCUE OF ASTRONAUTS, AND THE RETURN OF OBJECTS LAUNCHED INTO OUTER SPACE

The Agreement on the Rescue of Astronauts, the Return of Astronauts, and the Return of Objects Launched into Outer Space does not deal directly or indirectly with the problems of space debris. Its sole purpose is to ensure aid to astronauts in distress and protect them from exploitation if they land in a foreign country. The part dealing with the return of space objects was included to ensure that spacecraft that landed in a foreign nation would be returned to the original owner and not held by the country in which it landed. This treaty is not applicable to space debris.

8.1.3 CONVENTION ON INTERNATIONAL LIABILITY FOR DAMAGE CAUSED BY SPACE OBJECTS

The second treaty that could apply to the problems associated with space debris is the Convention on International Liability for Damage Caused by Space Objects. This treaty clarifies who is liable for space activities. Two forms of liability were created depending on where the damage due to a space object occurs. Since the treaty was primarily concerned with the damage done on the Earth from either an attempted launch or from returning spacecraft, liability for damages to people or property on the Earth or to aircraft caused by space activities is absolute. This means that a country that causes damage to the assets of another country as a result of its space activity is liable for this damage, regardless of fault or negligence. The two articles that could apply to space debris are Article II and Article III.

Article II

> A Launching State shall be absolutely liable to pay compensation for damages caused by its space objects on the surface of the earth or to aircraft in flight.

Article II makes the launching nation absolutely liable for damage on the surface of the Earth or to an aircraft in flight caused by its space activities. There is no fault required by the launching country for compensation to be mandated. This was similar to other laws covering "ultra-hazardous activities" where responsibility rests solely on the parties carrying out such activities. Launching nations have the duty to protect people and property on the Earth.

Article III sets out the law for damages done to space-based objects.

Article III

> In the event of damage being caused elsewhere than on the surface of the Earth to a space object of one Launching State or to persons or property on board such a space object by a space object of another Launching State, the latter shall be liable only if the damage is due to its fault or fault of the persons for whom it is responsible.

Here liability is not absolute but requires fault on the part of the country or the operator.

It is questionable if a collision between an uncontrolled piece of debris and an operational satellite could be considered the fault of the original owner of the debris piece. One may be able to convince a court that irresponsible acts such as the Westford Needles Experiment when thousands of debris were placed in orbit might constitute fault, but to convince someone that a collision of a satellite with a discarded object or used rocket booster would constitute fault is definitely not assured. Legitimate cases could be made for either side. For example, would a collision between an uncontrolled expended booster and an active controlled satellite be the fault of the launching nation of the booster or of the satellite? The nation owning the satellite is the only nation that could have avoided the collision by maneuvering the satellite and therefore may be considered liable.

One approach that has been advanced to solve this issue is to hold nations absolutely liable for damage caused by all objects they place in space. Under this scenario if two satellites collided, each nation would be responsible for the replacement cost of the satellite of the other nation. This would have serious negative effects on the development of outer space due to the very large potential liability for any objects placed in space. The launch of a single satellite could make a nation liable for billions of dollars if that satellite collided with an expensive system such as the United States Space Station or Space Shuttle. The United States would be liable for only the replacement cost of the satellite lost. In the event that the satellite was non-functioning this sum would be zero.

In any event before fault or negligence can be determined the country that owned or produced the debris must be identified. As pointed out earlier there is less than a one in ten chance of a collision occurring with a tracked space object versus an untracked space object. This makes the possibility of identifying the country of origin a small probability event.

One possible method of assessing the liability of debris of unknown origin may be to assess it in proportion to the amount of debris created by each country[61]. In the State of California there is legal precedent for this type of action in the Sindell vs Abbott Laboratories Case. In this case, product liability was assigned according to market share to the major producers of a drug that caused birth defects. This however is a state precedent and to date does not apply to federal cases. To apply this reasoning to space debris on an international basis would require significant re-interpretation of the treaty and international law. The Sindell vs Abbott case would provide a basis for someone who has lost a satellite to debris to sue the United States and the Soviet Union since they are the major producers of debris. However, there is no court that has sufficient jurisdiction over the United States and the Soviet Union to preside over such a case. The possibility of a case at least trying to use this argument in US courts is high given the potential multimillion dollar payoff of damages for a replacement satellite.

The United States and the USSR would oppose any change in the interpretation of this section because if they did agree to a more strict liability for debris, they would be primarily responsible for any damages caused by debris already in orbit. The potential liability to the US and USSR under this type of scenario is very large when future spacecraft fail due to space debris impacts.

Another serious question about the application of this treaty to the space debris problem is the fact that it refers to damage done by a space object. The term space object is not adequately defined. Article 1(d) states "the term 'space object' includes component parts of a space object as well as its launch vehicle and parts thereof." Questions as to whether space debris constitutes

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61 Reynolds, Glenn and Merges, Robert (1989) *Outer Space, Problems of Law and Policy*, Boulder, Colorado: Westview Press, p. 177.

space objects were never addressed during negotiation of the treaty.[62] During the negotiations several countries suggested that an appropriate definition of a space object would include "articles on board the space object and articles detached, thrown or launched, whether intentional or unintentional."[62] The final agreement does not reflect this language and reflects a more narrow interpretation.[62] Because of the lack of specificity, it is unclear as to what types of debris can be considered space objects and are subject to the liabilities outlined in the treaty.

Many of these details are usually determined through application of the law and its clarification through case law. To date the treaty has only been invoked once for damages caused by the re-entry of parts from a Soviet nuclear powered satellite.

As it stands this treaty does not provide an adequate means of controlling the production of space debris nor the liability of damage caused by debris in orbit. Many approaches have been proposed to solve problems with liability caused by debris, but they have not been accepted by the international community and therefore are not enforceable.

8.1.4 CONVENTION ON REGISTRATION OF OBJECTS LAUNCHED INTO OUTER SPACE

The third treaty which may address the legal aspects of space debris is the Convention on Registration of Objects Launched into Outer Space. This convention mandates that all countries keep accurate records of what they places into orbit so that liability can be assessed if some harm occurs as a result. Unfortunately this is only required at the time of launch and the records are not required to be updated if the satellite breaks into numerous pieces. There has been no requirement for nations to list absolutely every item that it places in space. Operational debris and other small objects that are too small to detect are not reported. Even so the United States attempts to keep track of all objects larger than 10 centimeters, including data on the country of origin.

The pertinent parts of the treaty that could apply to space debris are reproduced below.

Article II

> 1) When a space object is launched into Earth orbit or beyond, the launching State shall register the space object by means of an entry in an appropriate registry which it shall maintain. Each launching State shall inform the Secretary-General of the United Nations of the establishment of such a registry.

Article III

> 1) The Secretary-General of the United Nations shall maintain a Registry in which the information furnished in accordance with Article IV shall be recorded.

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[62] Baker, Howard A. (1988) Liability for damage caused in outer space by space refuse. *Annals of Air And Space Law, Vol. XIII*, p. 206.

2) There shall be full and open access to the information in this register.

Article IV

Each State of registry shall furnish to the Secretary-General of the United Nations, as soon as practical, the following information concerning each space object on its registry:

(a) Name of the launching State or States;

(b) An appropriate designator of the space object or its registration number;

(c) Date and territory or location of launch;

(d) Basic orbital parameters, including:

(i) Nodal Period

(ii) Inclination,

(iii) Apogee,

(iv) Perigee

(e) General purpose of the space object.

Article VI

Where the application of the provisions of this Convention has not enabled a State Party to identify a space object which has caused damage to it or to any of its natural or judicial persons, or which may be hazardous or deleterious nature, other State Parties, including in particular States possessing space monitoring and tracking facilities, shall respond to the greatest extent feasible to a request by a State Party, or transmitted though the Secretary-General on its behalf, for assistance under equitable and reasonable conditions in the identification of the object. A State Party making such a request shall, to the greatest extent feasible, submit information as to the time, nature and circumstances of the events giving rise to the request. Arrangement under which such assistance shall be rendered shall be subject to agreement between the two parties concerned.

While the idea of registration makes sense for large spacecraft, it does not work practically with small debris. Satellites and large debris objects are routinely tracked by the United States and the USSR and all objects in the US catalog are matched to their launching states. Therefore it is relatively easy to determine a particular cataloged spacecraft's origin, but if the object can not be matched to an originating state it is not included in the catalog.

Cataloging debris is not an easy task. When a booster explodes it can create hundreds of trackable debris and thousands of objects that can not be tracked. Even though these smaller objects can cause significant damage to spacecraft, since they are not trackable it is extremely difficult, if not impossible, to trace them back to a particular event or to the country of origin. This severely limits an injured party's ability to collect damages from another country.

Also the indications that a satellite has collided with debris may not be apparent. The first symptoms of a collision would be the failure of some or all of the spacecraft systems. Such failures would be hard to distinguish from failures due to other problems. In addition it would be extremely difficult to determine the orbital parameters of the piece of debris that caused the damage, the minimum information required to allow one to trace the object back to a particular owner.

Article IV provides a basis for a country that has suffered damage to request help from countries, such as the United States or the Soviet Union who have space tracking equipment, to identify space objects that can not be identified otherwise. While this part of the treaty was really meant to provide assistance in determining what country is responsible for damage on the surface of the Earth, it can be applied to the problems associated with space debris. Again this will be of limited use because less than one tenth of the dangerous objects in orbit are tracked.

8.1.5 THE MOON TREATY

The Treaty Governing the Activities of States on the Moon and Other Celestial Bodies (The Moon Treaty) was agreed to in 1979. This treaty represents many of the problems that have developed in the years since the early 1970s with achieving consensus on space policies. Pressure from the UN General Assembly to come to an agreement resulted in eventual agreement on the treaty, but the nations then failed to ratify and enact the treaty. To date only seven nations have ratified the treaty, none of which are space-faring nations. The United States Senate refused to ratify the treaty in 1980 and has not discussed the treaty since.[61] For practical purposes, this treaty does not constitute a legitimate part of international space law. At any rate the Moon Treaty does not address space debris directly or indirectly.

8.2 Other International Organizations

In addition to UNCOPOUS, there is one other international organization that has authority over aspects of space that may apply to the problems of space debris -- the International Telecommunications Union. One of the oldest international organizations, the International Telecommunications Union has authority over the radio frequencies used by satellites and the geosynchronous positions assigned to various countries. Its current authority comes from the 1982 International Telecommunications Convention. The ITU organizes administrative conferences either on a global or regional basis to assign radio frequencies and geosynchronous orbit slots. The regulations adopted at these administrative conferences are annexed to the International Telecommunications Convention and have the force of treaties at the international level.[63] The ITU is designed to maintain and extend the international cooperation to improve the use of telecommunications.

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[63] United Nations (1986) *Space Activities of the United Nations and International Organizations*, New York: United Nations, p. 75.

The major activities of the Union are to effect allocation of the radio spectrum, coordinate efforts to reduce interference, foster international cooperation, coordinate space telecommunications, and promote safety through communications. The last broadly defined activity of the ITU is to "undertake studies, make regulations, adopt resolutions, formulate recommendations and opinions, and collect and publish information concerning telecommunication matters."[64] This could be interpreted as giving ITU a limited role on space debris since space debris is a general threat to the satellite telecommunications industry. However this is a very broad statement and could not be used to enforce space debris mitigation regulations.

To date the ITU has not directly addressed the issues of space debris or the removal of satellites from the geosynchronous ring at the end of their useful lives. This however could be a proper forum to discuss the subject at least as it applies to the geosynchronous ring.

8.3 Domestic Space Law

In the United States there is no judicial or regulatory authority on space issues. This results in the existence of a number of different organizations that have partial regulatory powers over space and space-based resources. The main agencies involved in the regulation of space include: NASA, the Department of Defense, the Department of Transportation, the National Oceanic and Atmospheric Administration, and the Federal Communications Commission. Other organizations that could become involved in the space debris issue are the International Trade Commission and the Environmental Protection Agency.

8.3.1 NASA AND DOD

The main role of NASA and the Department of Defense in space debris mitigation is to regulate their own activities. Other organizations such as the Department of Transportation and the National Oceanic and Atmospheric Administration do not have regulatory authority over NASA or the Department of Defense. In the United States most commercial launch operations are conducted either by NASA or the Department of Defense from their launch sites and require significant support from both organizations. If these organizations refused to support launch activities of missions that would create an unacceptable amount of debris, they could do so.

NASA and Department of Defense both have the authority to require debris mitigation practices on any satellite or launch vehicle that they purchase. This can be done though requirements specified during the proposal or contract negotiations stage. Debris mitigation within the Department of Defense and NASA is a matter of policy and not a matter of law or regulations.

8.3.2 DEPARTMENT OF TRANSPORTATION

The Commercial Space Launch Act of 1984 authorized the creation of the Office of Commercial Space Transportation and gave it broad authority to license all commercial space launches from the United States or by any US citizen or company from within the United States. Section 6 of the Commercial Space Launch Act clearly states that any launch from the US or by any US person or organization from anywhere except in a foreign country is controlled by this Act and requires a license to launch or operate.

Commercial Space Launch Act

> Section 6 (a)(1) No person shall launch a launch vehicle or operate a launch site within the United States, unless authorized by a license issued or transferred under this Act.
>
> Sec 6 (a)(2) No United States citizen...shall launch a launch vehicle or operate a launch site outside the United States, unless authorized by a license issued or transferred under this Act.
>
> Sec 6 (a)(3) No United States Citizen...shall launch a launch vehicle or operate a launch site at any place which is outside the United States and outside the territory of any foreign nation, unless authorized by a license issued or transferred under this Act. The preceding sentence shall not apply with respect to a launch or operation of a launch site if there is an agreement in force between the United States and the foreign nation which provides that such foreign nation shall exercise jurisdiction over such launch or operation.
>
> Sec 6 (b)(i) .... this Act shall not apply to the launch of a launch vehicle or the operation of a launch site in the territory of a foreign nation by a United States citizen...

Section 6 also gives the Department of Transportation authority to stop a launch because of its payload even after a license has been issued.

> Sec 6 (b)(1) The holder of the launch license under this Act shall not launch a payload unless that payload complies with all requirements of the Federal law that relates to the launch of of a payload.
>
> Sec 6 (b)(2) If no payload license, authorization, or permit is required by any Federal law, the secretary may take action under this Act as the Secretary deems necessary to prevent the launch of a payload by the holder of a launch license under this Act if the Secretary determines that the launch of such a payload would jeopardize the public health and

safety, safety of property, or the national security interest or foreign policy interest of the United States.

Section 6, paragraph B, sentence 2 clearly states that launches can be halted for the safety of property. This could be interpreted to include the property potentially damaged by a large amount of space debris. Any actions of this type are subject to judicial review as outlined in Section 12, paragraph b.

> Sec 12 (b) Any final action of the secretary under this Act to issue, transfer, deny the issuance or transfer of, suspend, revoke, or modify or to terminate, prohibit, or suspend any launch or operation of a launch site shall be subject to judicial review provided in chapter 7 of title 5, United States Code.

A major limitation in the power of this act for space debris mitigation purposes exists in section 21, paragraph C which states that the act does not apply to space launches or operations carried out by the United States for the United States, which include all NASA, Department of Defense, NOAA, and intelligence organizations' satellites. These excluded launches are the vast majority of space launches by the United States.

> Sec 21 (c) Nothing in this Act shall apply to -
> (1) Any -
> (A) launch or operation of a launch vehicle,
> (B) operation of a launch site, or
> (C) other space activity, carried out by the United States on behalf of the United States...

Associated regulations were promulgated and published in the Federal Register on February 26, 1986. The regulations require a safety review and a mission review prior to issuing a license. The safety review focuses on the applicant's safety operations, including launch site, procedures, personnel, and equipment. The mission review is the procedure that identifies issues affecting the national interests and international obligations that are associated with a space launch. Section 415.25 of the regulation lists the required information for a mission review. Section 415.25 (b) specifically lists debris issues as part of the requirement for passing the mission review.

> 415.25 (b) The applicant must submit a flight plan and staging data sufficient for evaluating such factors as the potential for land overflight, impact of spent stages, and debris issues.

Another part of the mission review is the payload determination which is made by the Director. This is required when the payload is not licensed, authorized or issued a permit required by another Federal agency to be launched.

415.27 Payload Determinations.

The Director must determine whether to prevent the launch of a payload for which no license, authorization or permit is required by Federal law because to launch such a payload would jeopardize public health and safety, the safety of property, or the national security or foreign policy interests of the United States.

These regulations provide the Office of Commercial Space Transportation with relatively broad powers to regulate what industry places in orbit. However any ruling must be justifiable in court in the event of an appeal of the determination. Without a clearly stated policy or strong evidence of the seriousness of the orbital debris problem, it will be difficult to convince a judge that a few additional objects in orbit will cause significant increase in the risk to property or national security and would justify halting a multimillion dollar space program that a commercial venture has proposed. This would be especially hard if the United States were not enforcing debris reduction policies on its own Department of Defense or NASA satellites.

The Commercial Space Launch Act of 1984 allows for a mechanism to regulate debris-producing commercial launches through the review process that it has established prior to licensing. Yet its power to refuse to grant a license because of the generation of a small amount of debris is questionable because no formal policies or standards for space launch have been adopted. Any determination against a launch company would be subject to judicial review. Because of the lack of set guidelines and because of the actions of other federal agencies, any such refusal would in all probability be found arbitrary and could be overturned by the courts.

8.3.3 NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Under the Land Remote-sensing Commercialization Act of 1984, the National Oceanic and Atmospheric Administration is responsible for licensing all remote sensing satellites prior to launch. The Act states in the section findings that "certain government oversight must be maintained to assure that private sector activities are in the national interest and that the international commitments and policies of the United States are honored."[64] This authorizes NOAA to refuse licenses to remote-sensing systems that are "not in the national interest". It could be argued that debris-producing satellites are not in the national interest. However, it would be difficult to justify not launching a new satellite because of a small amount of additional debris when considering the benefits achieved by advanced remote sensing satellites. NOAA would have

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[64] Land Remote-sensing Commercialization Act of 1984 Section 101 (14).

to start denying potential debris producing satellites as a matter of policy before additional satellites are designed and built that would conform to a policy of debris minimization. To date NOAA has not done so.

In July 1987, NOAA promulgated regulations titled Licensing of Private Remote-sensing Space Systems. These regulations are designed to promote the development of commercial remote sensing space systems while preserving the national security interests and meeting the international treaty obligations of the United States. One part of the information required by the application procedure is the proposed method of disposition of any remote sensing satellites owned or operated by the applicant. This could be expanded to include any debris created during its launch or operations.

The Remote Sensing Act and its associated regulations allows the Secretary of Defense to undertake a national security review and the Secretary of State to undertake an international obligation review prior to licensing. In addition, the regulations allow for any other agency to object to the license if it finds that the application does not comply with any law or regulation in its area. The national defense review is meant to screen the missions to make sure that they do not provide information to an adversary about the US or its allies that could be harmful to national security. Nothing is said about space debris dangers. The review for international obligations as shown earlier does not impose any strict debris mitigation practices. As a consequence the Remote-sensing Act and its associated regulations do not provide an adequate means of controlling debris. Once again it only applies to a small percentage of the space launches and does not apply to United States government missions that make up a vast majority of the US remote sensing missions.

8.3.4 FEDERAL COMMUNICATIONS COMMISSION

The Federal Communications Commission (FCC) is responsible for the licensing and regulation of commercial communication satellites as outlined in the Communications Act of 1934 as amended.[65] The Federal Communications Commission is responsible for the assignment of radio communication frequencies and it controls US slots in geosynchronous orbit. Satellites fall under the FCC regulations because they are the modern-day radio stations that the FCC was designated to regulate.

The commission has the authority to establish the rules of and condition for licensing a new communication satellite. It also has the authority to designate where a satellite in geosynchronous orbit may reside and has the authority to direct the satellite to be moved with a 30-day notice.[65] This authority derives mainly from considerations of the electrical interference the FCC is designed to regulate and could not legitimately be used to authorize debris reduction regulations.

[65] Meredith, Pamela (1991) Legal implications of orbital debris mitigation practices: A survey of options and approaches, *American University Journal of International Law and Policy*, **6**, (Winter 1991):205.

Any basis the FCC may have to regulate the creation of debris or disposition of old satellites is based on the possibility that these objects may interfere or collide with other operational satellites that the Commission is assigned to regulate and secure.[65] Since the deployment of a single communications satellite creates a small amount of debris, the possibility of one of these objects colliding with an FCC-regulated satellite is very small. Therefore such an eventuality could not be used to justify a broad-based debris mitigation policy on the part of the FCC without significant re-interpretation and expansion of the law. Additionally the FCC would only be authorized to monitor and license US communications satellites, which constitute only a small part of the overall number of satellites launched each year. With changes in the Communications Act and FCC regulations, the FCC could effectively regulate debris created by aggressive (and potentially large space debris producing) ideas such as the Iridium mobile communications program[66] and other satellite communications programs. However the prospects for change in the laws governing the FCC are small. Efforts to update the half-century old Communications Act to reflect the current situation in the telecommunications industry have been stalled in Congress since 1980.

8.3.5 OTHER DOMESTIC ORGANIZATIONS

8.3.5.1 Environmental Protection Agency (EPA)

The National Environmental Protection Act (NEPA) gives the EPA authority to act when activities effect the domestic airspace. Activities such as launches that pollute the air or possible back contamination of the Earth from space would fall under the EPA's mandate. It is unclear or doubtful whether EPA's authority continues into space, and could address the issue of space debris.

8.3.5.2 International Trade Commission (ITC)

The ITC has no direct authority on space debris. However, if the United States were to impose high cost debris mitigation requirements on domestic satellites and launch services, the ITC could be asked to intervene if other countries did not institute such policies and stole significant market share from the US companies. But the effectiveness of this type of intervention is questionable because a large number of launch services are procured by foreign countries. The US could impose restrictions on sales of US made satellites to nations refusing to institute debris mitigation practices. However this could result in other countries receiving contracts to make the satellites.

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[66] Iridium Mobile Communications program is a constellation of 77 satellites designed to provide world-wide cellular telephone communications. It has been proposed by the Motorola Corporation. "Iridium-like Constellations Abound," *Orbital Debris Monitor*, 1 July 1991, p. 11.

8.3.6 STATE LAW

States can regulate activities within their borders provided the regulation does not counteract national laws. Florida has also used its state laws to halt some space activities. One example is the case of the Celestis Group that wanted to launch the remains of 10,000 people into earth orbit for a cosmic burial. The Office of Commercial Space Transportation had already issued the group a launch permit. The State of Florida used a law requiring that a cemetery have 15 acres and access to a paved road to halt the development of the operation.[60] I do not believe this case was the true purpose of the law, and I do not think it will apply in other potential space debris cases.

8.4 Contract Law

There are avenues open in private law to enforce debris mitigation practices. For instance, the space insurance industry assumes the risk of losses due to space debris. If the insurance industry wanted to insist as part of insuring a satellite that it conforms to a debris mitigation program, it could do so. However, the space insurance industry is not that farsighted. One of the concerns of the industry is to exercise influence only over the sector of space activities that it insures. Government space launches would not be covered under any insurance mandated restrictions. Also, the cost of space insurance is presently very high, and placing additional restrictions may force other companies to self-insure as Intelsat has in the past.

8.5 Conclusion

Existing international and domestic laws do not adequately address the problems of space debris. Treaties are vague when describing duties to protect the space environment. Domestic regulations are designed to foster commercialization of space and not to address the problems of space debris. The patchwork responsibilities of agencies both nationally and internationally make any interpretations of existing laws and treaties apply to only a section of the space industry. In general the existing laws are inadequate to regulate and control the problems associated with space debris.

9. POLICY ISSUES AND CONCLUSIONS

There have been several ideas of how to reduce the space debris problem. Any attempted solution will require an understanding of the problem and a consensus of what to do about it. This section will look at the possibilities of: active debris removal from orbit; improvements in the Space Surveillance System; effects of anti-satellite weapons on the Space Surveillance Systems; debris mitigation practices; and the domestic and international policy aspects of the debris problem.

9.1 Active Debris Removal Options

A possible solution to the space debris problem is to collect the debris though some means and return it to Earth. Many such removal options have been suggested, however this is not a viable alternative at this time or in the near future. The debris is scattered in a vast number of different orbits. Any system intended to collect these objects would have to carry a very large amount of fuel to accomplish the changes in velocity required to intercept the debris.

One such concept that has been advanced calls for the Space Shuttle or some type of Orbital Maneuvering Vehicle to chase down and collect debris. This, while noble in conception, is also not practical for debris in low-Earth orbit. The changes in velocity required to match the velocities of a variety of orbiting objects are so large that they are not within the realm of current or future engineering programs or funding projections. The cost of a highly maneuverable system would far outweigh the replacement cost of any satellite that may be saved by the removal of the debris by the system. The cost of such a system is not justified by the slight reduction in the threat of orbital debris at low altitude that would be accomplished.

Active removal mechanisms for the geosynchronous orbit are more feasible. Active debris removal may be possible in this case by the use of a system similar to the recently cancelled Orbital Maneuver Vehicle (OMV). The geosynchronous orbit is unique since the relative velocities between objects on it is small. One such OMV could collect a number of satellites and move them to a higher altitude with a relatively small amount of fuel. This could be used to remove inactive satellites or rocket boosters from the geosynchronous ring if they could not be removed by other methods. This would be practical only with large objects having relatively well-known orbital parameters. A higher number of smaller objects, such as those generated by a satellite fragmentation, will be spread over a large area and the time and fuel required to collect hundreds of objects will be impractical. This indicates that remedial action would have to occur before any satellite breakup.

Debris sweepers have been proposed, and a few have even been patented. Concepts such as large balloons filled with foam that sweep out unwanted debris, large paddle wheels with absorbing material that collect debris as they travel, or large conducting tethers to attach to debris and sling it back towards Earth have all been advanced. These ideas, while intriguing, are not practical or even possible at the present time. The size of the object that would be required to collect a significant amount of debris to make a difference in the debris population is on the order of 30 kilometers in diameter. Even if such a satellite were possible, the chance of having an operational satellite hit this object would be greater than that of the operational satellite hitting the debris that the absorbing body is intended to collect. To conclude, removal of debris from low Earth orbit appears both impractical and not cost-effective at least in the foreseeable future.

9.2 Improving the Performance of the Space Surveillance Network for Debris Avoidance

Another way to decrease the possibility of orbital collisions is to improve the performance of the Space Surveillance Network to allow it to provide accurate warning of collisions. For a comprehensive collision avoidance system based on the Satellite Catalog to be effective, the catalog must include the vast majority of the dangerous objects in orbit. Anything else would involve incalculable risk if it generated a false sense of security in near-Earth space.

A quick method to evaluate the performance of the Space Surveillance Network is to look at the Satellite Catalog as a function of time. By comparing the time of known break-ups with the appearance of related objects in the Satellite Catalog, it is possible to gain a sense for the time required to find different-size objects. Figure 59 shows the number of objects cataloged as a function of time since the 1961 Omicron breakup discussed earlier. The large increase at the beginning of the graph reflects the fact that most large objects were quickly identified. The gradual rise over time reflects the improved performance of sensors. But the latest increase after 1986 is due to improvements in tracking technology, changes in operations, and to the orbital decay of the objects.[7] Objects from the Omicron breakup are still being identified 30 years later. The objects currently being identified are on the order of 10 centimeters in diameter. Cataloging smaller debris is not currently attempted due to inherent limitations of the radars and bureaucratic aspects of the Satellite Catalog. Breakups today are cataloged much more quickly than they were in the past, but further improvements in sensor technology will undoubtedly show a continued increase in the number of cataloged objects from the Omicron breakup.

As shown in Section 5 the Space Surveillance System is limited in its detection ability by its radar and optical sensors; however, the system's detection capability is not the only limit on object size included in the Satellite Catalog. Certain bureaucratic problems further limit the cataloging of debris for inclusion in the Satellite Catalog.

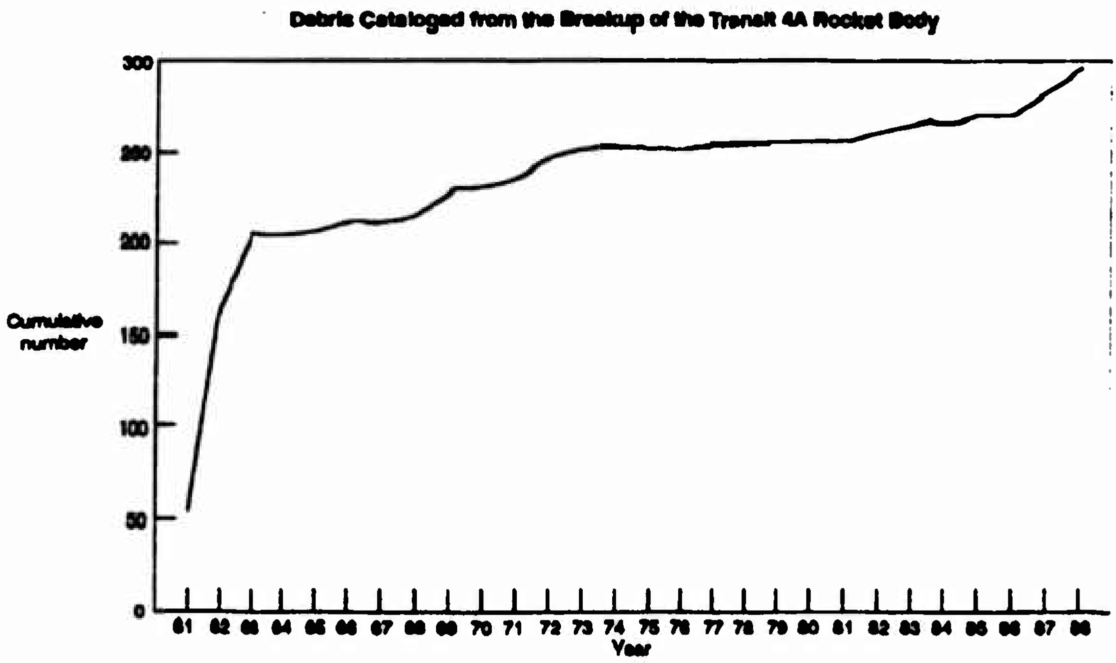

Figure 59. Cataloged Transit 4A Debris Over Time[7]

9.2.1 BUREAUCRATIC ASPECTS OF THE SATELLITE CATALOG

Not every object that is capable of being detected or is even detected by the Space Surveillance Network is included in the Satellite Catalog. For an object to be included in the Satellite Catalog, it has to pass certain "operational" criteria. These criteria include the ability to be easily tracked by the Space Surveillance Network, to have a relatively long life in orbit, and to be identifiable with a known launch from a specific country.[57] Objects that do not fulfill these three criteria are not included in the catalog. In April 1990 there were 354 objects in orbit that did not meet these criteria but were included in the analyst's catalog (the official Satellite Catalog plus objects that are tracked but not included in the Satellite Catalog).[57] The problems in identifying a large number of uncorrelated objects are due to limits of manpower and computer resources. To evaluate these problems it is essential to look at the method used to process detections.

9.2.1.1 Processing Detections

The manner in which the Space Surveillance Center processes the information is as important a factor in the detection and tracking of small space objects as the detection capabilities of the tracking equipment of the Space Surveillance Network. When an observation is made by a sensor and sent to the Space Surveillance Center, it is first correlated with the known objects in the catalog. If it does not correlate with any object in it, it is placed in a separate data file. As a measure of the volume of these uncorrelated observations, in two weeks (1 -14 August 1989), US Space Command made 1495 uncorrelated observations of space objects.[67] Human operators then try to determine what objects are multiple detections of the same object. If they can identify what seems to be the same object, they can form an initial orbit determination, which is required to direct other sensors to make additional measurements and thus achieve a final orbit determination which is required for inclusion in the Satellite Catalog.

This slow and manpower-intensive process constitutes a log-jam in the complicated system of space debris tracking. If too many uncorrelated detections are reported, then trying to match multiple observations with a single object becomes too difficult. When this occurs the database of uncorrelated targets is typically deleted and the process is started over with only new observations.[68] According to Space Command officials this is a recognized problem, but few are willing to devote the required resources to solve it. It is estimated that at any one time 50 additional space objects could be cataloged.[69] Figure 60 shows differences in the calculated flux per square meter of tracked objects included in the official Satellite Catalog and the Analyst Set. These are derived from the normal Space Command Satellite Catalog and from an analyst's data which includes additional objects that do not meet all the criteria for the official Satellite Catalog.

9.2.1.2 Observation Time Required for Uncorrelated Objects

In order to determine the orbit of an uncorrelated object in a single observation, a reasonable amount of the orbit must be observed. This reduces the errors due to range and Doppler uncertainties caused by the passage of radars waves through the ionosphere. Space Command's rule of thumb is that 5.5 percent of the orbit must be observed to get a reasonable orbit determination. During such an observation the mechanically steered radars and the optical sensor are not able to pursue other missions. Phased array radars can simultaneously track these objects and accomplish their other missions by dedicating only a small portion of the available radar power to tracking the object.

67 Personal notes from Space Debris Meeting at AFSPACECOM, 2 February 1991.

68 Told in private conversation with space command officials, 28 May 1991.

69 Personal interview with John Clark, Air Force Space Command, 28 May 1991.

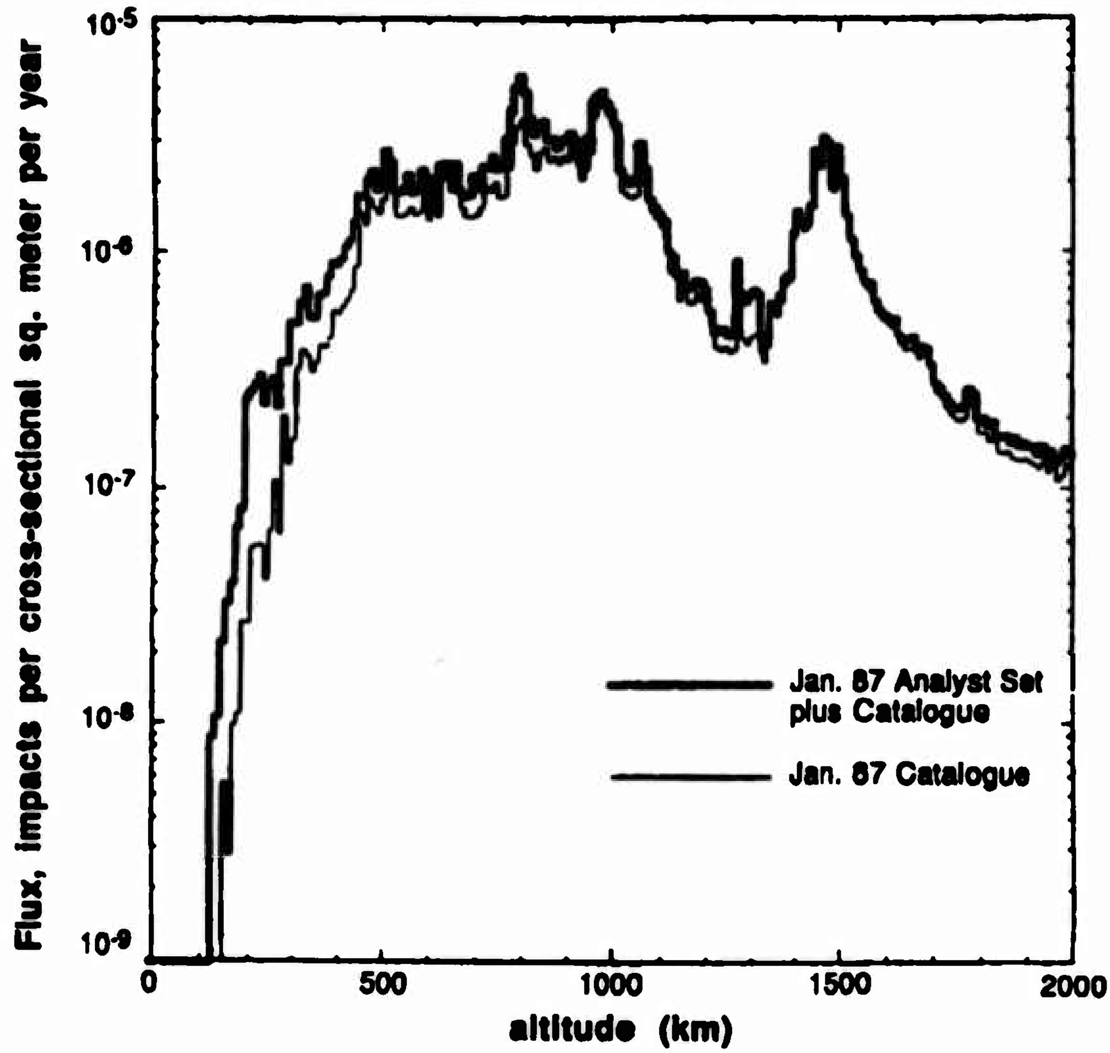

Figure 60. Comparison of Flux Arising from the Population of the Analyst Set and the Satellite Catalog Compared to the Satellite Catalog Alone[17]

This initial orbit determination is adequate to permit re-acquisition of an object over the next several orbits. After several orbits, the position errors from the initial orbit determination become too large and the object is too far from the predicted position for sensors to re-acquire them using the orbit prediction. Additional observations from other sensors provide information at other parts of the orbit, allowing error analysis programs to determine more accurately the orbital element sets prior to including the object in the Satellite Catalog.[46] Table 18 shows the approximate track length as a function of orbital period required to build a preliminary orbit from a single observation.

Table 18. Minimum Duration Observation Required for Initial Orbit Determination as a Function of Orbital Period[46]

Altitude (Kilometers)	Object Period (Minutes)	Minimum Duration of Observation (Minutes)
300	90	5
500	95	5.2
1,000	105	5.8
5,000	200	11
20,000	347	19
20,000	710	39

9.2.1.3 Effects of a Large Number of Uncorrelated Targets

Due to this limited ability to handle large numbers of uncorrelated targets, another practice occurs that runs counter to the requirement of identifying and tracking all space objects. According to Space Command officials, the detection threshold on several of the radar systems in the Space Surveillance Network is purposely degraded to avoid detecting objects that cannot be identified.[69] The sensitivity of the receiver systems is purposely turned down. This allows operators to report only returns from the larger space objects, totally ignoring returns from smaller objects. This is done in an attempt to limit the number of uncorrelated returns that would otherwise overload the cataloging process. This is such a systematic practice that in the case of one of the main space surveillance systems, the FPS-85 radar at Eglin Air Force Base, Florida, the transmitted power is purposely reduced because the radar does not have adequate gain adjustments on the receiver end to limit the number of small objects detected.[69]

If a systematic approach were used to catalog these marginal objects, the number of uncorrelated returns could be reduced. According to Space Command officials, a program has begun there to develop a graphic representation of these uncorrelated objects that hopefully will reduce the time required for correlation and orbit determination. However, this program is more than a few years away from being operationally capable. Even that, however, will not end the problem: there is a non-technical issue that also needs to be addressed.

9.2.1.4 Method of Evaluation of Space Surveillance System

There is another reason why Space Command is reluctant to catalog small objects. The problem can be traced in part to the manner in which officers inside Space Command are rated and how the performance of their organizations is measured. The number of lost objects is presented to the commander of Air Force Space Command as a gauge of how well the Space Surveillance Network is functioning. The units responsible for maintaining current orbital parameters on objects in the catalog are down-rated and judged poorly in proportion to how many objects they "lose" in a particular week. To lose an object means that expected observations of that object have not occurred in over 48 hours. This routinely occurs during periods of high geomagnetic activity and solar storms, when atmospheric drag significantly alters the object's expected course. During a severe storm in 1988, Space Command "lost" 1500 objects in orbit. Although many of the weaknesses of the system have been identified and fixed, the memory of that period has commanders concerned about the numbers of unaccounted objects.[69]

Since smaller objects are harder to detect, and therefore easier to lose, Space Command is very reluctant to include these objects in their official catalog. This results in even more uncataloged objects. This explains why at any one time there are at least 50 objects that have been detected that could be cataloged, but to date have not been. A group inside Space Command is trying to start an additional type of catalog to keep track of these smaller objects, but they are having a difficult time convincing superiors that it should be done in this period of limited personnel and declining defense resources.

9.2.1.5 Priority of Space Debris Measurements

Priority of requirements is an important factor in the allocation of radars and optical sites to various tasks. Since small debris is more difficult to detect, they require longer observation times. But at the present time since debris measurements are a very low priority mission compared to other Space Command tasks, the amount of radar and sensor time required to keep accurate orbital parameters of debris is not allocated to this task. Since Space Command does not have atmospheric models that can accurately account for increased drag caused by geomagnetic or solar storms, they allocate additional observation time for higher priority satellites when such storms occur. During such periods space debris measurements and tracking take a secondary role. By the time space surveillance operations return to the normal level of activity and the sensors are again able to dedicate time to tracking the smaller debris, some of these may be so far from their predicted orbits that they can not be found by sensors searching areas near their earlier orbits. These objects would then be lost and would need to be re-acquired through the same method as an uncorrelated object.

These problems are compounded by the fact that the observation time of operational sensors such as the GEODSS sites is being reduced due to the overall Department of Defense budget cuts and reduction in force requirements being mandated by the Defense Management Review. It is no wonder that the commanders are reluctant to expand their catalog and consequently responsibilities.

9.2.2 UPGRADES IN COMPUTER CAPABILITY

Correlating observations of uncataloged objects with any of the tracked objects and continually updating orbital parameters of 7000 objects is an intensive computational process. The current Space Command computer systems process up to 40,000 observations each day. The expected upgrades of these systems will not provide significant additional support for catalog maintenance, but later upgrades are expected to increase the capability to approximately 150,000 observations each day, nearly 4 times the present capability.[46] But considering the estimated number of small objects in orbit as seen by GEODSS and other optical means, this upgrade in computational capability may still be inadequate to catalog every object that poses a threat to satellites. Increasing the capability of the computer system by a factor of 4 will still not allow the cataloging of dangerous debris larger than 1 cm, which is estimated to be a factor of 10 larger than the cataloged population.

9.2.3 LIMITS IN COMMUNICATION PATHS

In addition to the limits on computer resources, there is another limiting factor that will preclude significant increases of the size of the Satellite Catalog to include smaller debris. The communication links between the Space Surveillance Center and its remote sensors are usually operating near their capacity. Doubling the size of the catalog will require data transmission rates that may overload the communications links. This could occur during times of increased loads, during solar storms for example, when activity is at its peak. Space Command believes it can double the size of the catalog without major upgrades to their communications systems, but any increases beyond that would require a large investment in communication links and computer systems to handle the increased load.[46]

9.2.4 CONCLUSION ON SATELLITE CATALOG AND DEBRIS MEASUREMENTS

What would alleviate the danger presented by space debris is a firm commitment from Space Command to track all detectable objects in orbit and dedicate the resources and funds necessary to accomplish this mission. It also must look at the manner in which it evaluates the performance of the various tracking facilities. If commanders are going to be judged on the number of objects lost, they will continue to refuse to add ever smaller objects to their responsibilities. However, if they were evaluated on the basis of how many new objects they found and cataloged or on how many objects they did observe, a mechanism of encouraging a more complete cataloging of space objects would be established. A result of these organizational difficulties is that the Space Command Catalog fails to include between 8 and 35 percent of the detectable objects in orbit as established by specialized tests with the PARCS radar system that could detect objects only as small as 8 cm.[6] Further, optical systems such as GEODSS and some specialized systems that can track objects with sizes of the order of 1 cm in low-Earth orbit, have detected 8 times as many objects as included in the official catalog.[6]

Because of the difficulties and the limitations of the Space Command Satellite Catalog, combined with the limitations associated with detection capabilities and orbital prediction routines described in Section 5, the Space Surveillance System does not provide an adequate method for collision avoidance. Sole reliance on the existing system to provide adequate collision warning to critical space systems invites disaster.

9.3 Studies on Anti-Satellite Weapons Effects on the Space Surveillance System

Two studies have been completed that examined the effects of anti-satellite weapons engagement on the Space Surveillance System. One study, done by MIT's Lincoln Laboratories, looked at the effect of ASAT debris generation on the Space Surveillance Network.[70] The other study was conducted for the General Officer Steering Group and looked at similar areas but focused on the command and control aspects of anti-satellite engagements.[71] Both of these studies identified similar problems with the observation and processing capability of the Space Surveillance Center. The Lincoln Laboratory study used six ASAT engagement scenarios in which only 906 debris fragments were produced, corresponding to an increase by a factor of 5 in the activity of the Space Surveillance Network .[70] This test used very optimistic debris assumptions -- judging from the fact that many on-orbit breakups have created more than 500 pieces of debris each. Hypervelocity collisions such as those that would occur in an anti-satellite engagement are expected to produce many more objects, and spread them more widely.

During computer runs to simulate a space war and its effect on the Space Surveillance System a data processing problem emerged. With just two anti-satellite weapon intercepts, the Space Surveillance Network became overloaded and was unable to process the high number of uncorrelated objects. Planned upgrades of the computer systems at the Space Surveillance Center, while providing more capabilities, are not significantly better at this type of task. It would certainly not be an order of magnitude more capable than the current system, the improvement required to track the debris from ASAT engagements.[72]

During the Command and Control Evaluation Study, two anti-satellite engagements (with 128 post attack debris objects each) "taxed the system so severely that the system was not able to update the number of required target trajectories during the study period of two hours."[70] The study also found that the stress on the system due to uncorrelated targets grows linearly with time as additional sensors report uncorrelated returns. Analysts attempted to correlate the debris particles with the original parent satellite and to treat the entire debris cloud as a single entity in an attempt to streamline the processing of the incoming data.

The ASAT scenario is very close to what occurs just after an on-orbit breakup. The typical procedure is to allow the uncorrelated debris from a breakup to spread for several revolutions prior to even attempting to identify and catalog individual pieces. ASAT testing and use will cause a significant amount of debris production. This could have very serious consequences on the debris population and probably cause the onset of the Kessler Effect. In response to these concerns, the United States has made space debris reduction a major focus of its anti-satellite weapons

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70 Cox, L.P., Burnham, W.F., Pololck, J.K. and Seniw, W. P. (1991) ASAT debris generation: effect on Space Surveillance Network, Proceedings of the 1991 Space Surveillance Workshop, Lincoln Laboratory, 9-11 April 1991.

71 (1989) Space Surveillance/Command and Control Evaluation Study in Support of the OSD Anti-satellite (ASAT) General Officer Steering Group (GOSG), 24 May 1989.

72 Personal notes from Space Debris Meeting at AFSPACECOM, 22 February 1991.

program. It is not obvious however, that an anti-satellite weapon can be designed that can destroy its target without making a large amount of debris.

9.4 Long Term Solution: Mitigation of Debris

The best way to minimize the possibility of collisions is to limit the future growth of orbital debris. Debris can be controlled by a number of procedures including booster venting, de-orbiting satellites, and clearing geosynchronous orbits. A vast amount of the orbital debris has been created by intentional or unintentional satellite or rocket body breakups. This type of fragmentation debris makes up 50 percent of the 7,000 trackable objects. Used rocket bodies contain residual fuel at the completion of their mission. Explosion of this fuel creates thousands of fragments of all sizes with added velocity in addition to the original spacecraft velocity.

Three possible approaches are suggested as the first steps to adopting debris mitigation policies. The first and foremost is to increase awareness of the orbital debris problem. The second is to perform an economic analysis to determine if a market-based solution can be adopted. And the third is to consider seriously the possibility of government regulation to control further proliferation of debris in space.

9.4.1 AWARENESS OF THE PROBLEM OF SPACE DEBRIS

By increasing the awareness on the dangers of space debris it is possible to change the behavior of commercial and government launching practices. Peace groups, armed with knowledge about space debris, were able to make forceful arguments against the US anti-satellite weapon system, for example.

There are additional approaches once a country becomes concerned about the effects of space debris. One such avenue is the Outer Space Treaty under which any nation can protest space experiments that may harm the common use of space. An example of such an experiment that most likely would not be allowed to happen was the ill-conceived Westford Needles Experiment. This experiment occurred early in the space program and showed little regard for its long-term effects on the space environment. In this experiment scientists dispersed thousands of 2-inch needles in orbit in order to form an artificial ionosphere for a communication experiment. These needles were released at 4,000 km and will remain in orbit for several thousand years. With the recent publicity and concern of the space debris environment, political pressure could be brought to bear on countries attempting such experiments, urging them not to carry them out.

Other recent actions that have shown little regard for their effects on the space environment are the intentional destruction of satellites during several US and USSR anti-satellite tests. These tests have created thousands of debris particles that could easily have been avoided. Of the 530 tracked objects (greater than 10 cm) in orbit following the US ASAT test against the Solar Wind satellite, 251 are still in orbit. It is estimated that several thousand hazardous untrackable pieces of debris between 0.1 and 10 cm that were generated by the test are still in orbit.

Significant pressure has been brought to bear on the two countries as their goals and concerns for their ASAT programs have changed significantly. Currently, a major concern for the US anti-satellite weapons program office is the production of space debris. Significant efforts are being undertaken to minimize the creation of long-term space debris by anti-satellite tests or the use of such weapons. Systems are being studied with offset aim points to avoid debris producing direct collisions. Systems containing mylar sheets with embedded pellets to avoid a large number of free flying debris in a post attack environment are being considered. This is in direct response to the pressure exerted by groups opposed to the anti-satellite weapon which base their opposition at least partly on its effects on the space environment.

Fortunately the problem of debris is now becoming apparent to space-faring nations. The United States, the USSR, and the European Space Agency (the three main space users) have all begun programs to quantify conditions of the debris environment and to study the deleterious effects of space debris. These groups have begun to recognize the long term effects of space debris. Unfortunately they are not the only relevant actors. Other nations are rapidly developing launch capabilities and have begun placing payloads, and debris, in Earth orbit. Countries that have launched satellites include China, Japan, India, Israel, Brazil, and Iraq. These countries and others that are developing the technology represent a significant challenge to an international regulatory environment that is not designed to control the population of space debris.

There are other problems within countries that have multiple launching groups. For instance, in the US there are three users of space: the Department of Defense, NASA, and the commercial space launch industry. A clear consensus on the effects of space debris and the necessary steps required to control it has not emerged as yet among the three. NASA and DOD have formed a joint working group to study the problem and develop a future policy, but the industry is not participating.

The concerns of the Department of Defense are different than those of NASA. Department of Defense is developing a number of systems that may significantly increase the hazard of space debris if used or deployed. Two such systems are the ASAT and SDI. While some concerns about space debris have influenced the latest designs of the ASAT weapon system, it is difficult to believe that it will not create large number of debris during operation or tests. SDI as envisioned by some will significantly increase the total mass and the number of objects in orbit, which will result in more collisions with existing or additional debris and increase the possibilities of the onslaught of the Kessler Effect.

NASA's concerns center around the Space Station and the Space Shuttle. Both are high priority systems and their vulnerability to space debris is a major concern, due to the presence of people in them. The Space Station is particularly vulnerable to space debris because of its large size and long mission duration.

A number of international meetings of scientists have tried to sort out the problems and define the salient issues. Problems they identified include the lack of data on debris between 0.1 cm and 10 cm, absence of practices to mitigate debris producing events, and the lack of legal controls to enforce space debris mitigation policies.

9.4.2 DEBRIS MITIGATION PRACTICES

Debris mitigation is by far the most cost effective method of eventually reducing the long term effects of space debris. As with toxic wastes, it is much easier and cheaper to control adverse effects of space debris before they are released into the environment. As shown in Section 3, most of the debris has been generated by old satellites, operational launch debris and fragmentation of rocket boosters and inoperative satellites.

9.4.2.1 Operational Debris

Older satellites such as the Defense Meteorological Satellites produced a relatively large amount of operational debris while modern geosynchronous satellites rarely produce any. Mitigation of operational debris can be designed into satellites if it is the policy to do so. For instance, retaining bands, pins and cutaway cables can be replaced with contained mechanisms that do not produce debris. One problem with this mitigation method is getting the very conservative space industry to change their methods of operation. The industry is loathe to change methods and approaches that have already been repeatedly flight proven in the past.

The cost of the actual design changes and hardware is small; however, new methods require extensive testing and flight qualifications which increase the cost of a system significantly. The price of a potential failure of a simple debris mitigation item is the cost of the entire satellite. Satellite insurance companies are very sensitive to new technologies and techniques; their sensitivity indirectly increases the cost of testing new debris-mitigation processes and hardware.

As a result, industry is not likely to change previously designed satellites to lessen the effects on space debris. The presence of space debris does not impact the industry's profitability. If a satellite is destroyed by space debris, the industry will likely be asked to provide a replacement satellite and launch services, which would earn additional revenues for it. But in the long run the loss of several satellites by the communication industry may drive the costs of satellite-based systems higher, making ground-based fiber optic lines more attractive to many customers, and thus indirectly pressure the aerospace industry to introduce debris reduction measures.

9.4.2.2 Rocket Bodies

Rocket bodies make up 16 percent of the tracked objects in space. These are released after they deploy satellites to their proper orbits. Some satellites have internal motors that circularize the orbit and then retain the additional fuel for station-keeping purposes. This eliminates the requirement for an additional booster for final orbit insertion. In addition, boosters for transfer to geosynchronous orbit could be placed in a low perigee orbit that would cause them to re-enter the atmosphere in a few years as opposed to a few hundred years. Small changes in velocity could be accomplished using residual fuel which would cause the booster to re-enter quickly, provided the engineering and guidance was done prior to the launch. But changes in rocket systems require extensive testing. Again, as with operational debris, much of the cost is not with the design as with the risk of failure. If a rocket system fails because of the debris mitigation efforts of a launch service, the result for the satellite company is the same: loss of a significant amount of money.

The major impediment to these types of changes is the launch industry. Major changes in operation are not going to be made unless they are decisively encouraged by profit motive or regulation.

9.4.2.3 Inactive Payloads

Inactive payloads make up 21 percent of the tracked debris in orbit. Many of these payloads have simply outlived their useful lives and depleted their fuel supplies. If placed in orbits with lifetimes approximating their expected lifetimes, these systems could re-enter the atmosphere relatively soon after completing their missions and not contribute to the long-term space debris problem. This is not practical for many missions, but for missions that are not altitude sensitive it would be feasible. An example of how system design consideration could be changed is the DMSP weather satellite. It is in a 1000 kilometer Sun-synchronous orbit which allows it to view the entire globe every 12 hours. With a lower altitude it would require a wider field of view to gain overlapping coverage for the entire world. A different mission scenario is to launch two satellites in lower orbit to allow for over-lapping coverage and provide a backup satellite in case one fails. Other possible options include providing fuel to de-orbit the satellite at the completion of the mission or to lower the perigee height, decreasing the orbital lifetime.

9.4.2.4 Fragmentation Avoidance

Explosions of expended rocket boosters have caused a significant amount of debris. The United States experienced a number of Delta II fragmentations prior to redesigning the booster to vent the fuel after placing its payload in orbit. This experience is being re-learned by each nation as they enter the launch business. The European Space Agency learned this after the loss of a Spot satellite. The Chinese learned it after the explosion of a Long March rocket booster in a high altitude Sun-synchronous orbit. The United States has taken aggressive action to help countries mitigate these problems. However the actions they can take in helping other countries with rocket technologies are limited because of the technology transfer restrictions to most countries.

9.4.2.5 De-orbiting

Many methods have been devised to de-orbit used spacecraft and rocket bodies. These have included using unexpended rocket fuel to lower the perigee altitude or using drag enhancement devices to hasten the de-orbiting process caused by atmospheric drag. An example of a type of drag enhancement device may be a large Echo 1 type balloon which can be inflated, increasing the effective area of the satellite. A large balloon could easily increase the drag by a factor of 10 and significantly increase the rate of orbital decay. Any such drag enhancement system adds weight and hence cost to a spacecraft. For most satellites the amount of weight is limited by the launch vehicle. Any additional weight required for debris reduction programs comes at the expense of payload or fuel.

Rocket-based de-orbiting requires a reserve amount of fuel at the end of a mission to accomplish a burn that will cause a lowering of the perigee altitude and cause the satellite to descend into the Earth's atmosphere. This again implies the additional weight of the fuel needed for de-orbiting is to be added to the spacecraft, replacing payload or mission fuel. De-orbiting an object from a 2000 km circular orbit to an elliptical orbit with a 2000 km x 100 km orbit requires a change of velocity equal to 455.8 meters per second. For a 2500 kilogram satellite, this requires 500 kilograms of hydrazine, the amount of fuel it takes to keep a geosynchronous satellite in its proper orbit for 10 years, clearly a large weight penalty.

9.4.2.6 Re-orbiting

Re-orbiting applies mainly to satellites in geosynchronous orbits. There are two methods for reducing the chances of collision with other spacecraft: the first is to place it near the stable points which would keep the satellites from drifting around the geostationary ring and the second is to boost the satellite slightly above the geosynchronous ring. The first proposed re-orbiting option is to place satellites in the stable points at 75 degrees East and 255 degrees East longitude. Any object in geostationary orbit will move around the geostationary ring, oscillating about the geopotential stable points unless controlled by east-west station-keeping. Placing inoperative satellites near these locations dampens the oscillations that as a consequence remain small. In the absence of any perturbations, such discarded objects would remain fixed over Panama and Malaysia without the requirement for East-West station-keeping. Satellites could be moved to these locations at the end of their useful lives or when they are near fuel depletion.

Objects so stationed will, however, be affected by perturbations from lunar and solar gravity and solar radiation pressure. Small velocity changes of the order of a fraction of a meter per second can cause large oscillations around the stable point.[73] Velocity changes of only 0.6 meter per second can cause oscillations of 25 degrees in longitude about the stable point. This oscillation would pose a threat to other satellites in the geostationary ring.

Placement of a large number of objects about the stable point would increase the chances of collisions between such discarded objects. Any collision would impart additional velocities to the resulting debris that would then spread over the geosynchronous ring, posing additional threats to satellites. This method would also render a number of the already crowded positions near the stationary points more hazardous and possibly unusable for other satellites.

Because of the extreme velocity and position accuracies required and the potential for collision between discarded objects, the stationary disposal option is not considered to be a satisfactory long-term storage solution for old satellites and boosters.

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[73] Chobotov, V.A. (1989) Disposal of spacecraft at end-of-life in geosynchronous orbit. Paper AAS 89-378 from the AAS/AIAA Astrodynamics Specialist Conference, 7 - 10 August 1989, Stowe, Vermont.

Another way to avoid collisions in the geosynchronous orbit is to boost a satellite from the geosynchronous orbit to an orbit slightly above the geosynchronous ring. This would significantly reduce the chances of it colliding with other objects. The spatial density at the geosynchronous ring is several orders of magnitude higher than on orbits only a hundred kilometers higher or lower, as shown in Figure 61. Velocity change requirements for a change in altitude of 200 kilometers is approximately 6 meters per second or approximately 3 kilograms of hydrazine per 1000 kilograms of satellite. This maneuver can easily be accomplished with existing thrusters.

Figure 62 shows a simulation of the perigee height of a satellite in a near circular orbit (eccentricity 0.001) 150 kilometers above geosynchronous orbit. The satellite is affected by solar and lunar gravity perturbations and solar radiation pressure. The perigee height shows a 24 kilometer per year variation with a longer-term 20 kilometer baseline change. This indicates that super-synchronous orbits are relatively stable and provide a long-term solution for geosynchronous debris.

The major problem with boosting satellites from geosynchronous orbits is the uncertainly as to when to accomplish the maneuver. Uncertainties about a satellite's lifetime are large. Satellites expected to last five years often last seven or eight. The main limitation to accurate predictions is the uncertainty about the remaining available fuel.

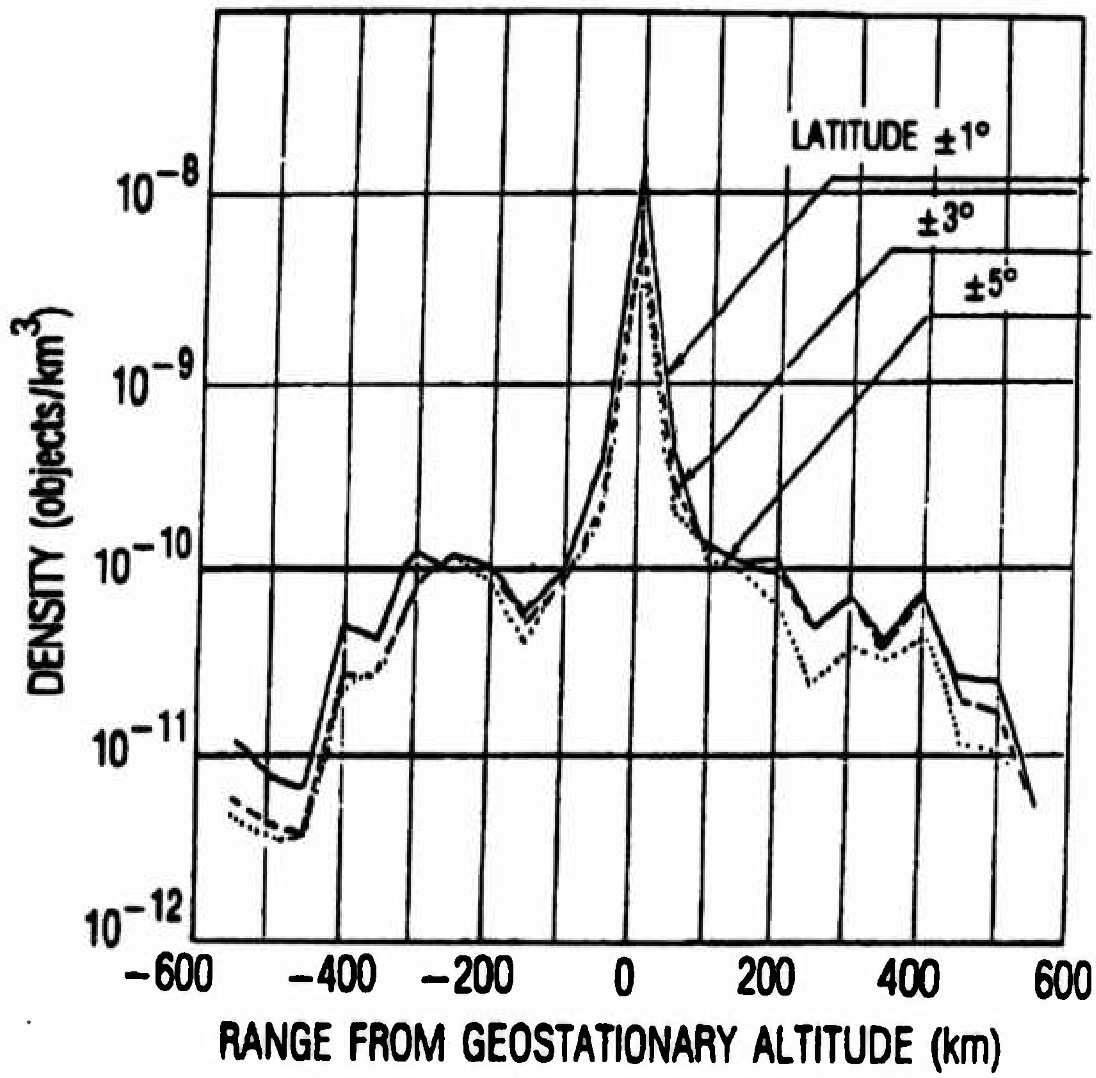

Figure 61. Geosynchronous Population Density[73]

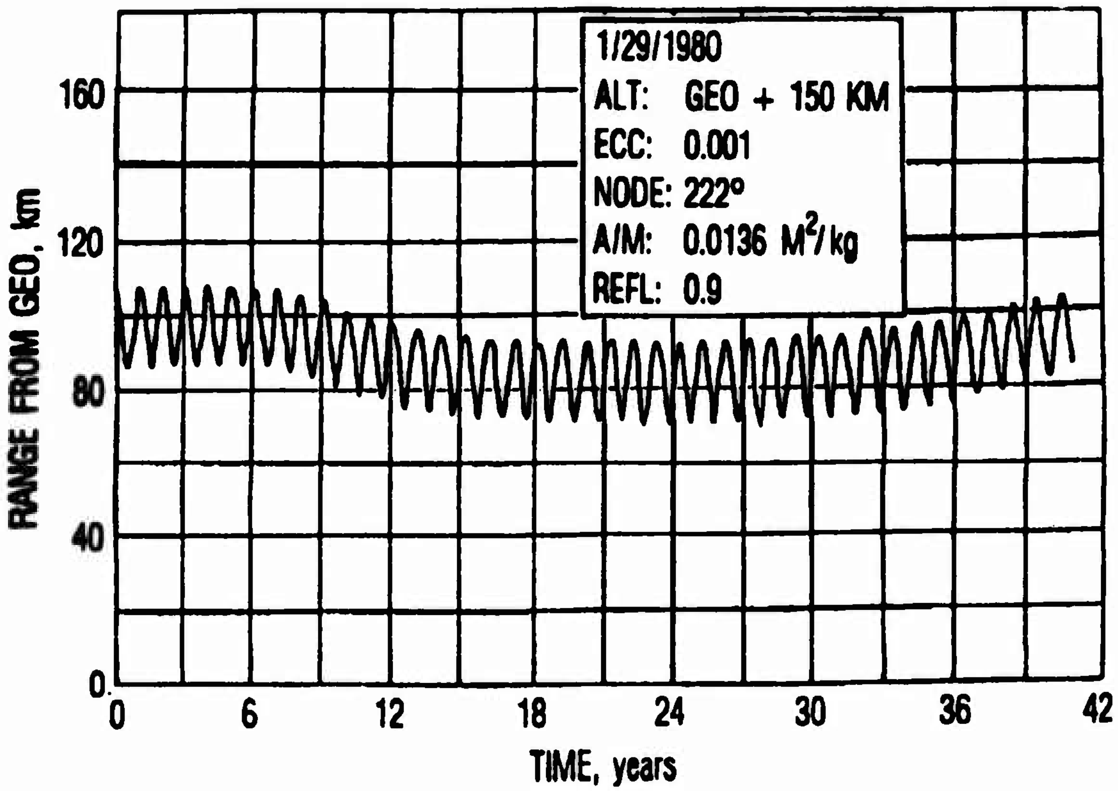

Figure 62. Perigee Drift in Super-Synchronous Orbit over Time[73]

The main problem inherent in super-synchronous orbit disposal is the fact that the amount of fuel remaining on-board a satellite is uncertain. Fuel gauges and metering systems are limited in their accuracy. To ensure enough fuel exists for the re-orbiting maneuver, a satellite company would have to use conservative estimates of fuel remaining and may remove the satellite from orbit several months or even a year prior to exhausting the remaining fuel. The fuel required is only on the order of 0.1 to 0.5 percent of fuel available. This requirement for fuel gauging in a zero gravity environment is an area of concern to the engineering community.

There are two primary methods for fuel gauging: measuring mass remaining in the fuel tank and integration of the amount of fuel used. Measuring mass or volume remaining in the fuel tank is an uncertain technique because of the uncertain distribution of fuel in a zero gravity environment. Volume or mass methods are limited to approximately 5 percent accuracies. Integration techniques are difficult for high accuracy measurements because of the accuracy required for flow and pressure readings as well as mixing ratios during burns. Integration techniques have been limited to approximately 3 percent accuracies. Newer fuel gauging techniques such as ultrasonic detection and super-critical storage radio frequency coupling show improvements over older methods but do not appear to reach the accuracies required for assuring altitude-raising maneuvers and depletion of all available fuel.

A possible method to allow for satellite operation until fuel depletion and to clear the geosynchronous orbit is to provide a second small tank with the required fuel for the desired increase in altitude. At depletion of the primary tank the satellite would have enough fuel to clear the geosynchronous orbit. The additional weight with this method would be small -- only the weight of the tank and fuel.

Any orbit raising maneuver should be carried out as a three or more burn maneuver to ensure that if fuel is expended before the maneuver is completed that the satellite does not cross the geosynchronous altitude. If a Hohmann[74] transfer were attempted and fuel were depleted during the first burn, the satellite would cross large areas of the geosynchronous ring at a relatively high velocity, significantly increasing its chances of colliding with other space objects.

Several countries and corporations have begun to remove satellites from the geosynchronous ring to create space for newer satellites. INTELSAT, the large international satellite communications firm, raised early satellites (Intelsat I, II and III) approximately 50 km above the geosynchronous altitude. Six of the seven INTELSAT IV satellites and two of the five INTELSAT IV-A satellites have been boosted out of geosynchronous orbit. NASA, NOAA, Telesat, RCA, ISRO, IMERSAT and EUTELSAT have all agreed to boost satellites at the end of their useful lives.[2]

Political question exists as to the will to accomplish mission-ending maneuvers. Would a country or company remove a "critical" satellite from geostationary orbit if it were running low on fuel and did not have a replacement satellite in orbit? This may be the case with the sole remaining National Oceanic and Atmospheric Administration's GOES weather satellite which has exceeded its expected lifetime by several years. What policies or regulations would encourage a company to boost a profitable communications satellite from orbit knowing that once it does it will lose the associated revenues?

Another problem with plans to remove satellites from geosynchronous orbit is that the survival rate of satellites over a ten year lifetime is only 85 percent. If a satellite is not functioning properly it may be impossible to command it to maneuver out of geosynchronous orbit. Catastrophic failure of satellites while on-orbit generates additional objects in the geosynchronous orbit each year even with the most stringent of debris mitigation programs.

9.4.3 ECONOMIC ANALYSIS OF DEBRIS MITIGATION

Debris mitigation practices do not add value to a satellite being delivered to orbit. At the present time, the odds are still good that a satellite will not be destroyed by space debris during its useful life. The threat to a particular satellite caused by a few extra objects in orbit from a single launch is negligible. The results of debris mitigation practices during a few launches will not make a significant difference. Since there is no financial benefit or marginal gain, there is no financial incentive to undertake any mitigation action. As mentioned earlier the space industry is a very conservative industry that does not change rapidly. This is evident in the fact that they are still using Titan missiles and Delta rockets designed in the 1950's to launch spacecraft. Change is made at a slow and careful pace. The cost of failure is significant, ranging from a replacement

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[74] Hohmann transfer is a two-impulse maneuver between two circular, coplanar orbits. It is the minimum energy transfer and uses the least amount of fuel for a given increase in altitude.

launch, to lost business because of reliability concerns, to higher insurance premiums. The extra cost of introducing new practices and hardware to reduce debris generation provides little or no additional benefits to the launch company.

Many of the debris reduction strategies would include significant changes in the operation and design of spacecraft and rocket systems. These changes do not come without cost and risk, and as a consequence they are avoided by the commercial sector.

9.4.3.1 Space as a Common Property Resource

Space is a common resource. No country or company has to pay for the use of space or for leaving objects in space. Because no one has to pay for the use of space, some externalities exist that are not taken into account when determining the true cost of the use of space. But cluttering space with debris has a social cost that is not being accounted for in the individual economic decision-making processes that undergird decisions to use space. As with any resource, companies and countries will utilize space until the marginal cost equals the marginal rate of return. At this point the usage will exceed the efficient usage for society because they are not including the net cost to society of their actions.

Each launch contributes to the debris problem and the more systems people launch into orbit, the worse the situation will get. This mandates that satellite designers in the future will be required to take extra precautions to mitigate the problem of space debris in orbit. This will cost additional money and increase costs for all. On the other hand, if debris continues to accumulate at an unchecked rate, it eventually will cause destruction of satellites and force expensive shielding measures, increased insurance premiums or debris removal mechanisms to be undertaken so that space could continue to be used. It is against these future costs of debris pollution that the costs of current mitigation efforts must be compared.

The legal entities that must be regulated are countries, corporations and international agencies. These entities are all driven by different motives, not all necessarily focused on profit. Factors such as prestige and scientific accomplishment may further erode any market-based solution to the space debris problem.

There are two methods for controlling a common resource. The first is to let one entity control the resource and set prices so as to ensure the most efficient use thereof. The price for the use of space could depend on the amount of debris left at the end of the mission since that is what reduces the value of the resource for everyone else. An agreed-upon price would be difficult to reach. Some countries would argue that they had not caused the original problem because they were not space-faring nations and should be allowed to pollute as much as other nations before they are charged. This is in line with arguments between third world and developed nations in areas such as greenhouse warming and chlorofluorocarbon reductions. In any case it is not possible to have a single corporation control space and set prices because nations would not agree to it and there could be no enforcement mechanisms.

The other solution for controlling a common resource is to have some form of governmental regulation that regulates the use of space in order to preserve it for future use. It is not clear that a single government or world body could be entrusted with control of space. The United States and the European Space Agency are unlikely to accept expensive debris mitigation policies on launch services if the nations with developing commercial space launch services such as China, the USSR, or Japan do not accept these additional expenses in an already extremely competitive launch industry. The nation or company that accepted expensive debris mitigation practices unilaterally may be pushed out of the launch business by pricing themselves out of the market. Because of this, any action must be taken on a global basis. There are only a relatively few (approximately 15) space-faring nations which would have to agree.

While compliance with debris mitigation could be monitored by US Space Command using their Space Surveillance Network and by the corresponding Soviet space surveillance network, enforcement prior to launch may be difficult. Countries such as the United States and the USSR may not allow inspection of secret payloads. However they may not have to since other enforcement techniques are possible. Inspection of design plans would be one. Detection of delinquent behavior could result in considerable international pressure to bring the culprit state in line. Threats or actions such as restricting access to advanced technologies and other space-related goods may be enough to keep them from breaking any agreements.

Regulation within the United States can be accomplished by the same inspection and design reviews prior to construction and by the issuance of a launch permit or export license for satellites to be launched on foreign launch vehicles. Laws exist that if re-interpreted could encompass debris mitigation requirements. This is not currently possible on the international level because as described in Section 8, the existing treaties that form international law do not adequately address the problems of space debris.

9.5 Domestic Policy Considerations

The United States is now the dominant space power and a prime producer of space debris. A major impediment to implementing any debris mitigation program in this country is that the United States does not have a single focal point for space activities. Instead the National Space Council, NASA, The Department of Defense, the Department of Transportation's Commercial Space Transportation office, the National Oceanic and Atmospheric Administrations, and the Federal Communication Commission, to name a few, are all involved with space utilization. This structure has made it difficult to come to a consensus on the problems of space debris. Even within each organization agreement on what to do has not been reached. Within NASA, the people working on the Space Station are very concerned with space debris and are urging actions to limit its production. At the same time other groups in NASA are launching satellites such as the Combined Radiation and Release Experiment Satellite (CRRES) that released 24 five to ten pound canisters into long-lived orbits. This internal conflict and lack of co-ordination exists in other organizations as well.

This fragmentation of the American space organizations has resulted in a confusing regulatory framework within which to initiate debris mitigation programs once a consensus is reached. Any policy that is instituted must cover all aspects of space activity, including DOD, NASA, and commercial activities. The possible cost of debris mitigation programs is an important issue. Re-design of spacecraft and rocket boosters, including associated testing and qualifications, requires significant amounts of money. Currently the United States faces a huge federal budget deficit and defense spending is being sharply reduced. Unless forced to, the Department of Defense is unlikely to allocate a larger share of money to the problems of space debris during periods of significant reductions in manpower and force structure. NASA is also undergoing a reduction of some of its operations and projects. The re-design and shrinking of the Space Station, and a reduction of 5,000 people in the Space Shuttle operations imply that NASA would likely opt to expend funds to lessen the impact of reductions on these high priority programs rather than address the space debris problem.

Commercial ventures such as the Iridium Mobile Satellite communications system are unlikely to initiate expensive debris mitigation programs on their own without regulation or guidelines. Any amount of money spent on debris mitigation would come directly off their profits. The mere probability of losing a satellite to debris will not in itself induce them to take voluntary space debris mitigation efforts.

The United States is currently trying to develop a private commercial launch industry to compete with the European Space Agency's Ariane rocket. The space industry is under intense competition from other foreign start ups such as the heavily subsidized Soviet and Chinese launches. Any expensive debris mitigation program that raises the cost of American launch services will force contracts to be awarded to foreign competitors who do not institute them. Consequently it is unrealistic to burden an industry which is considered an important aspect of American global leadership with uncompetitive burdens.

Like most environmental problems, space debris is not immediately apparent to most people. As a result the problem will continue to receive only minor support from the existing establishment, until some dramatic event occurs, such as the loss of a Space Shuttle or the Space Station, that would attract the attention of the American public and raise demands for action. But it may be already too late.

9.6 International Policy Concerns

Space debris is an international problem. It affects every nation's present and future ability to use space. Continued production of space debris will threaten certain orbits that are now used for weather prediction, intelligence gathering, remote sensing, communications, and scientific experiments. Loss of the use of these capabilities in space would have a dramatic effect on the world. Yet there are currently no international treaties or agreements that can be applied to the problem of space debris. Existing treaties are vague and open to interpretation. They do not provide any authority to anyone to enforce debris reducing regulation. A major concern is the development of space systems by developing countries such as China, and Brazil. Without specific international treaties or regulation, controlling the production of space debris by these countries will be difficult. The United States should and does provide assistance to these countries to aid in controlling on-orbit breakups of rocket boosters and satellites by transferring technology necessary to implement debris reduction measures.

International agreement must be reached to define what steps are required of all space launching countries to protect the near-Earth space. Without international agreement, countries trying to break into the commercial launch industry will have no reason or incentive to raise the cost of their launch services, which are heavily subsidized by their governments anyway, to avoid the production of space debris.

Negotiating a treaty to enforce debris mitigation will be difficult. As with the Montreal protocol dealing with ozone-depleting chlorofluorocarbons, developing nations will want an opportunity to build their industry under the same rules that the developed world promoted their space launch industry. Third world nations may argue that any treaty would keep developing countries from building space launch systems because of the higher cost of debris reduction strategies. This would not be a strong argument because debris reduction policies would cost very little compared to the cost of developing a launch system.

The possibility of negotiating a treaty through the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPOUS) is small. UNCOPOUS has been deadlocked on a number of treaties involving direct broadcast satellites, solar power satellites, nuclear power satellites, and remote sensing. The conflicts are not occurring among technologically advanced nations but between space powers and developing nations.

A space debris treaty does not necessarily have to be approved by all nations, since only nations with space launch capabilities would produce space debris. Limiting the treaty negotiations to this group could restrict the number of potential demands on the treaty process from third world nations that are unlikely to develop a space launch capability in the near future.

The United States is in the best position to promote such a treaty. As the sole remaining superpower and now as the premier space power, this nation should take the lead and push for an international treaty that calls for tight controls on the production of space debris. The United States has the resources to monitor compliance with such a treaty through its Space Surveillance Network. The United States has the most to gain from a space debris treaty and the most to lose if one is not adopted, because of its large space infrastructure. Only under the terms of such a treaty that imposed common debris mitigation requirements on all launches could individual nations enforce compliance with these requirements on their various government agencies and industry that utilize space.

In conclusion, Space Debris is a serious environmental problem with large economic, military, technical and diplomatic components. Actions need to be taken now in order to:

- determine the full extent of the orbital debris problem.
- accurately predict the future evolution of the debris population.
- decide the extent of the debris mitigation procedures required.
- implement these policies on a global basis via an international treaty.

Action must be initiated now, before the ominous onset of the Kessler Effect or the loss of critical space systems such as the Space Shuttle or the Space Station.

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Appendix A
Techniques for Optical Debris Measurements

There are a number of different techniques for making optical measurements of small debris. Some involve just staring vertically into the sky, waiting for objects to pass overhead. Others, in an attempt to increase sensitivity, direct the telescope along a predicted orbit to allow time integration of the signal of any objects that may be in that particular orbit. The staring and the tracking modes are discussed below.

A1 STARING MODE

In a staring mode the telescope's field of view remains fixed or is moved slowly at the sidereal rate. Image data is read from the Charged Coupled Device (CCD) or vidicon detector at the focal plane of the instrument and is recorded on video tape. Data is typically recorded at TV rates of 30 frames per second. At this rate the stars do not move in a given frame. Because of their angular velocities orbital objects will appear as streaks. Any object that crosses the field of view will be recorded on a number of frames, depending upon the angular velocity of the object and the field of view of the telescope. Elimination of stars and background can be done by subtracting sequential frames, leaving only the streaks of the moving objects.

Digital recording of this data is not currently possible. Instead, the data on the CCD is converted to a video signal and recorded on high quality S-VHS video tape. Later, this raw video data can be digitized to allow for computer based analysis.

The sensitivity of this method depends upon the angular velocity of the debris because the signal is spread over a number of pixels per frame. This method is independent of the direction of motion of the object and is as sensitive in detecting an object in a retrograde orbit as one in a polar orbit. The size of the detected object is determined by the optical signature, which is determined by assuming a value for an albedo and an atmospheric extinction. Calibrations of the instrument are made by looking at known star fields with calibration stars of known optical magnitude.

A2 TRACKING MODES

The primary purpose of tracking an object is to keep its image stationary on the focal plane, allowing the signal to be integrated over time, thus allowing it to be more easily detected against the background noise. Significant increases in sensitivity are possible with tracking methods. Mechanical or electronic tracking techniques can scan the sky at a fixed angular rate that is equal to the angular velocity of an object in a specific orbit. Any object with that velocity will remain fixed at a point on the focal plane since light from such an object will concentrate on only a few pixels, thus allowing for detections of fainter signals because the background noise is increasing only as the square root of the background signal. (The background signal is subtracted from each pixel. The statistical noise in each pixel is the square root of the background signal)

There are a number of methods to accomplish the tracking mode of operation. One is to mechanically drive the telescope at the desired angular velocity. A disadvantage of this mode is that once a volume of the field of view has been searched for only a fraction of a second, the chances of detecting additional objects in that same space are close to zero. The telescope must then change velocity to look at a different volume of space moving in that same orbit and then return to the matching velocity of the orbit of interest. This method of operation limits the amount of time spent making observations versus the amount of time maneuvering the telescope.

Another method is to use a movable mirror as a secondary mirror. This mirror scans the field of view of the telescope over a region without requiring the entire telescope to move. This allows for more accurate tracking and shorter delays between observations. It also reduces the vibrations caused by rapid changes in velocities of the telescope and eliminates the stresses placed on the mounts.

A third method of tracking is done electronically and is known as the time delay integration or TDI method. In this mode, the telescope is in a staring mode but the image is electronically shifted across the focal plane as the object crosses the field of view. Modern CCD cameras have the capability of shifting the signals from rows of pixels over time. The speed that the rows are shifted equates to a specific velocity, allowing the signal to be integrated on a single pixel. The direction of the object is determined by the orientation of the CCD detector with respect to the telescope. The signal is collected until it reaches the last row of the CCD. It is then read off the chip and transfered to tape for later analysis.

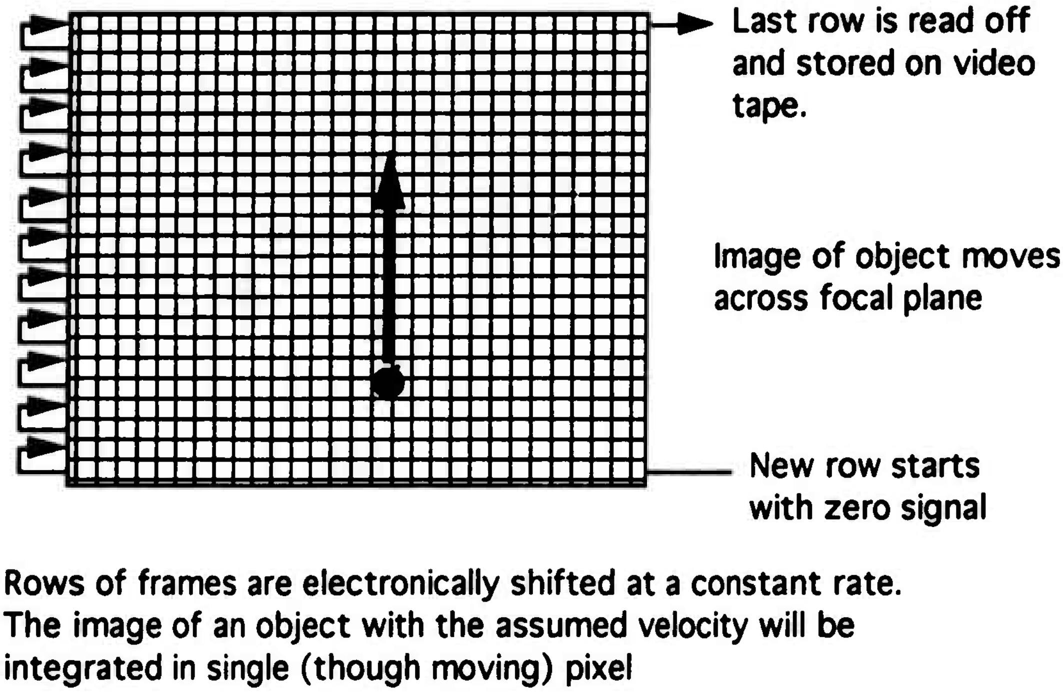

Figure A1. TDI Method of Tracking on the Charge Coupled Device (CCD)

In the TDI mode, the rate at which the rows are swept is determined by the angular velocity of the assumed orbit. This method, as opposed to the other two tracking methods, allows for continuous, uninterrupted measurements of objects in a particular orbit. Also, by using this method, significant reductions in the amount of data transferred are possible, allowing for real time analysis.

A3 TRADE-OFFS OF TRACKING METHODS

While the tracking mode offers significant increases in sensitivity, there are significant trade-offs to be made when using this mode instead of the staring mode. In the tracking mode, objects travelling at velocities other than the assumed velocity will require significantly greater signals in order to be seen since the signal is spread over a larger number of pixels than they would have been in the staring mode. Because of this negative effect on sensitivity for objects other than those in the particular orbit being searched, the "volume" of space searched by this method is significantly reduced. The volume of space searched inadequately defines the amount of debris that an experiment could observe. What is required is a method of characterizing the amount of volume and orbits that are searched. I will call this "phase space".

"Phase space" is an eight dimensional space. In this particular case these dimensions are the six orbital parameters (semi-major axis, inclination, eccentricity, longitude of ascending node, argument of periapsis, and the true anomaly), the size of the detectable objects and the time of the measurement. This phase space defines the orbits, debris sizes and times that have been searched by a particular measurement. Different experiments will search different volumes of this space.

An example of this phase space is seen in the differences in the amount of phase space observed in the staring and tracking modes. The staring mode of optical detection is equally sensitive to all objects regardless of direction of motion which then covers all semi-major axis, inclination, eccentricity, longitude of ascending node, argument of periapsis, and the true anomaly that pass through the field of view of the sensor. Tracking methods are very sensitive to objects travelling in the assumed direction; however, they are relatively insensitive to objects travelling in other directions. The tracking methods have viewed only those objects that have passed through the field of view that fall within a narrow band of altitudes, inclinations, right ascension, and eccentricities that correspond to the angular velocity that the telescope has scanned.

Both systems are limited to objects that cross their field of view during the observation period. Figure A2 compares the magnitude and direction of angular velocity, inclination and size covered by the tracking and staring methods. The magnitude of the angular velocity is a function of the orbital parameters semi-major axis, eccentricity, and true anomaly. The direction of the angular velocity is a function of the inclination, right ascension and true anomaly. For circular orbits angular velocity corresponds directly to the altitude of the objects.

Although the two measurements view the same volume of space for the same amount of time, they do not search the same amount of "phase space". The staring mode has observed a larger amount of phase space and a variety of orbits while the tracking method observes a small fraction of the objects that cross its field of view. Only by characterizing the phase space searched by each observation method can relative comparisons be made.

Because of the limited phase space which tracking systems can observe, tracking searches concentrate on orbits where large amounts of debris are known to exist. This significantly increases the likelihood of detecting objects. For example, since very few objects reside in retrograde orbits, it would not be prudent to start searching those orbits with tracking systems while neglecting the large number of debris that reside in polar or sun-synchronous orbits. In order to accurately interpret data from tracking observations, full consideration of the observed phase space must also be taken into account.

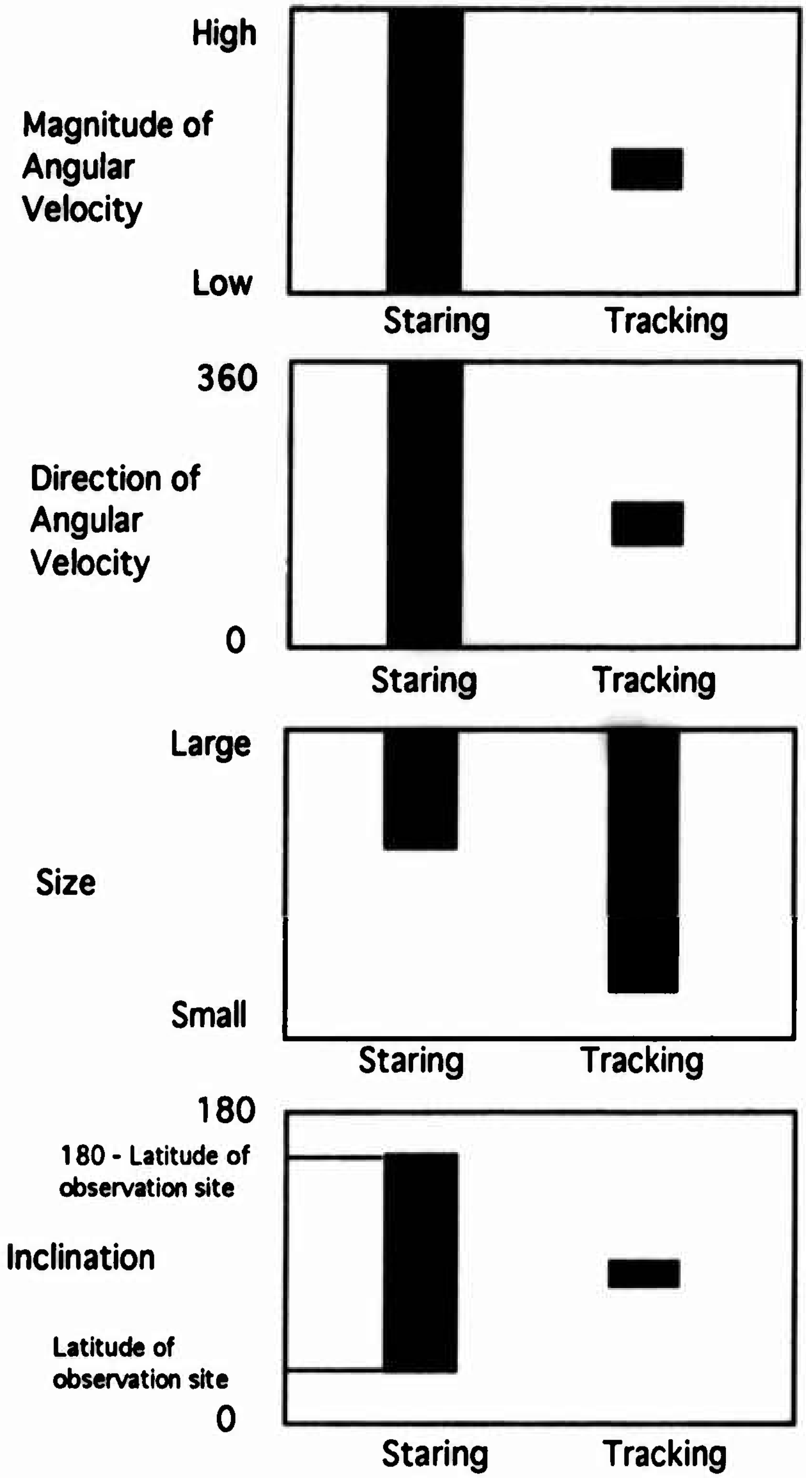

Figure A2. Relative Amount of Angular Velocity, Size and Inclination Observed in the Tracking and Staring Modes of Operations

A4 OTHER REQUIREMENTS FOR PHILLIPS LABORATORY

Phillips Laboratory was asked by Space Command officials to develop methods that could track objects in order to form preliminary orbits on debris in an effort to identify them with a particular breakup and to develop methods to study recent breakups in order to specify the number of fragments and the characteristics of orbital breakup of satellites. Two methods to accomplish these objectives are the stare and track method and the TDI and track method.

A4.1 Stare and Track

The concept of the stare and track method is to have one telescope stare vertically to observe debris, and when an object is detected the direction of motion is determined and a secondary telescope is moved to re-acquire the object. Secondary telescopes are available at many of the participating sites. The secondary telescope re-acquires the debris and tracks it in order to acquire accurate orbital and photometric data on debris.

The advantage of this approach is that it is sensitive to all inclinations and altitude debris. The staring mode has the highest probability of detection of larger random debris because of the larger phase space observed. The data from this mode of operation is also available for the post processing and data enhancement discussed earlier. Real time detection levels can be set near the noise level because false alarms can be verified quickly by the secondary telescope.

The disadvantage of this system is that it requires real-time streak detection at video rates. This, while not impossible, will require development.

For the other requirement to search for fragments from a recent breakup, the Time Delay Integration method with a tracking telescope would work well. Objects from a single recent breakup will be in roughly the same orbit. This allows the scanning modes to search the approximate orbit for smaller sizes.

A4.2 TDI and Track

The concept of TDI and Track is to make very sensitive measurements using the Time Delay Integration method of scanning and utilize a second telescope to make additional observations of detected objects to form accurate orbital parameters and collect photometric data. The scanning system can match the expected orbital velocity. Time Delay Integration moves the pixels on the chip instead of moving the telescope.

This system requires two telescopes, which are available at both the AMOS and the ETS sites. The advantages of this system over other scanning modes is that it provides continuous coverage of orbits of interest without requiring position changes or velocity changes with the telescope. Because of this there isn't dead time while the telescope is repositioned.

Appendix B
An In-depth Look at an Optical Debris Detection System

As an example of the techniques and problems involved with optical measurements the optical debris detection with the Wright Patterson 100-inch Collimator is described in this section. A detailed look at the Wright Patterson effort will provide an in-depth understanding of the issues and equipment involved with optical measurements. This effort is currently underway and is led by the Geophysics Directorate of the Phillips Laboratory at Hanscom Air Force Base, Massachusetts with KEO Consultants as an in-house contractor supporting the effort. Data collection will continue for the next 3 to 4 years.

The objectives of the Wright Patterson debris measurement program are to demonstrate the capability to gather data on debris down to 0.5 cm, to implement sensor and processing techniques that enhance detection sensitivity, and to provide modelling programs based on the new data. The Wright Patterson effort uses a passive optical sensor that relies on solar illumination of the debris. To make the optical measurements, the atmosphere above the collimator must be in the Earth's shadow while the debris is still illuminated. This limits the time available for debris measurement to short periods just after dusk and just prior to dawn.

Because of the nature of the measurement, both the size and the altitude must be inferred with several assumptions. The altitude is computed from the angular velocity, with the assumption that the objects are in a circular orbit. This assumption is appropriate for all but the higher eccentricity orbits. Size is determined from the optical signal intensity with the assumptions of an albedo or reflectivity of 0.08 and the object's altitude as determined from the angular velocity.

The core of the Wright Patterson equipment is an existing 100 inch (2.54 meter) diameter optical collimator developed for testing and producing large optical components for airborne or space-based imaging systems. The collimator is shown in Figure B1. The mirror focal length to diameter ratio is 6, providing a relatively fast optical system and a wider field of view than most astronomical telescopes (but smaller than other participating sites in the measurement effort). The large mirror, although it was unused for nearly 20 years, remains of outstanding optical quality.

This mirror is housed in a 12 story vacuum chamber in an isothermally temperature controlled building. Inside the 14 foot vacuum chamber is a 10 foot invar tube which limits the effects of any temperature variations. The top of the vacuum chamber is removable, allowing the collimator facility to be used as a large fixed telescope. Removable doors on the roof of the building were installed for the laser radar experiments done by the Geophysics Directorate and Wright Laboratories in 1989. The receiver is mounted at the F/6 port. A large turning mirror bends the image 90 degrees and out a port in the side of the vacuum chamber.

The core of the receiver system is an Imaged-intensified Charge Coupled Device (ICCD). The image is focused and reduced through a number of lenses onto the image intensifier. The image is then relayed to a CCD camera system. The output of the CCD is viewed on a video monitor and is stored on a S-VHS video tape. The receiver system schematic is shown in Figure B2.

The first three lenses, two achromat lenses and a Canon camera lens, reduce the image of the search volume from 54 mm to 25 mm at the image intensifier. The first lens is placed at the focal point of the collimator. The image intensifier is a 22 mm second generation inverted type. It has a gain of 55,000 with a visible gain of 20,000. The resolution is 36 pixels per millimeter.

The output image from the intensifier is then focused onto the CCD camera using a compound non-vignetting lens. This system does not cause a reduction in the image intensity as the edge of the field of view is reached. To accomplish this, a Rodenstock 100 mm/F1.5 and a Fujinon 25 mm/F0.85 relay optics are used. The Fujinon lens is used at F1.4 to reduce vignetting. The image size of the search volume at the CCD is 6.2 mm.

The CCD camera system is a commercially acquired Cohu type 6510. Its format is 6.4x4.8 mm with 739 horizontal and 484 vertical pixels. The resolution of the system is 560 horizontal and 350 vertical TV lines. The sensitivity of the system is 0.01 lux. For full video, 0.4 lux is required. While the 6.2 mm image will be centered on the CCD, some of the image will be lost on the shorter 4.8 mm sides, as shown in Figure B3.

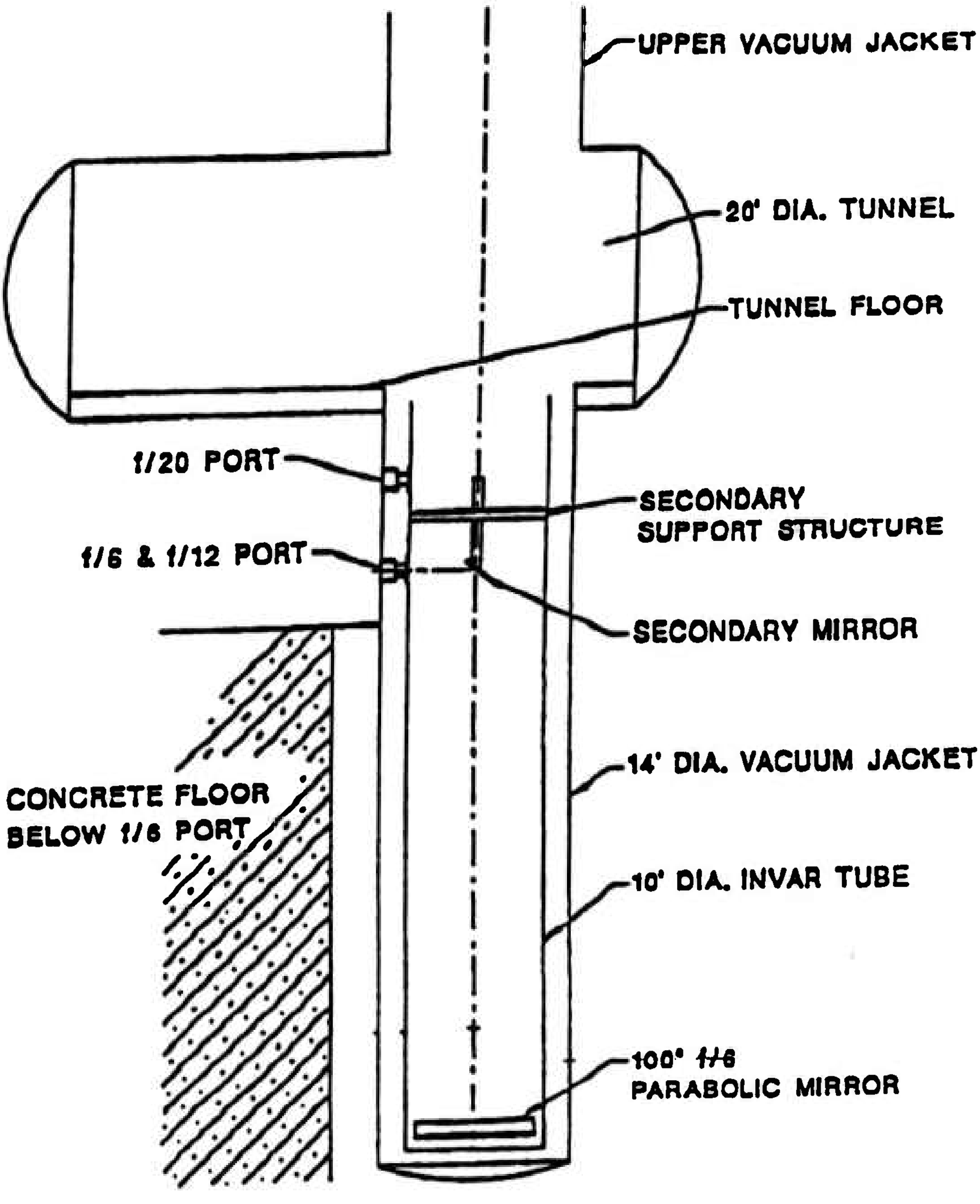

Figure B1. Wright Patterson 100-inch Collimator to be Used for Space Debris Detection. The detector is mounted at the focal plane located at the f/6 port

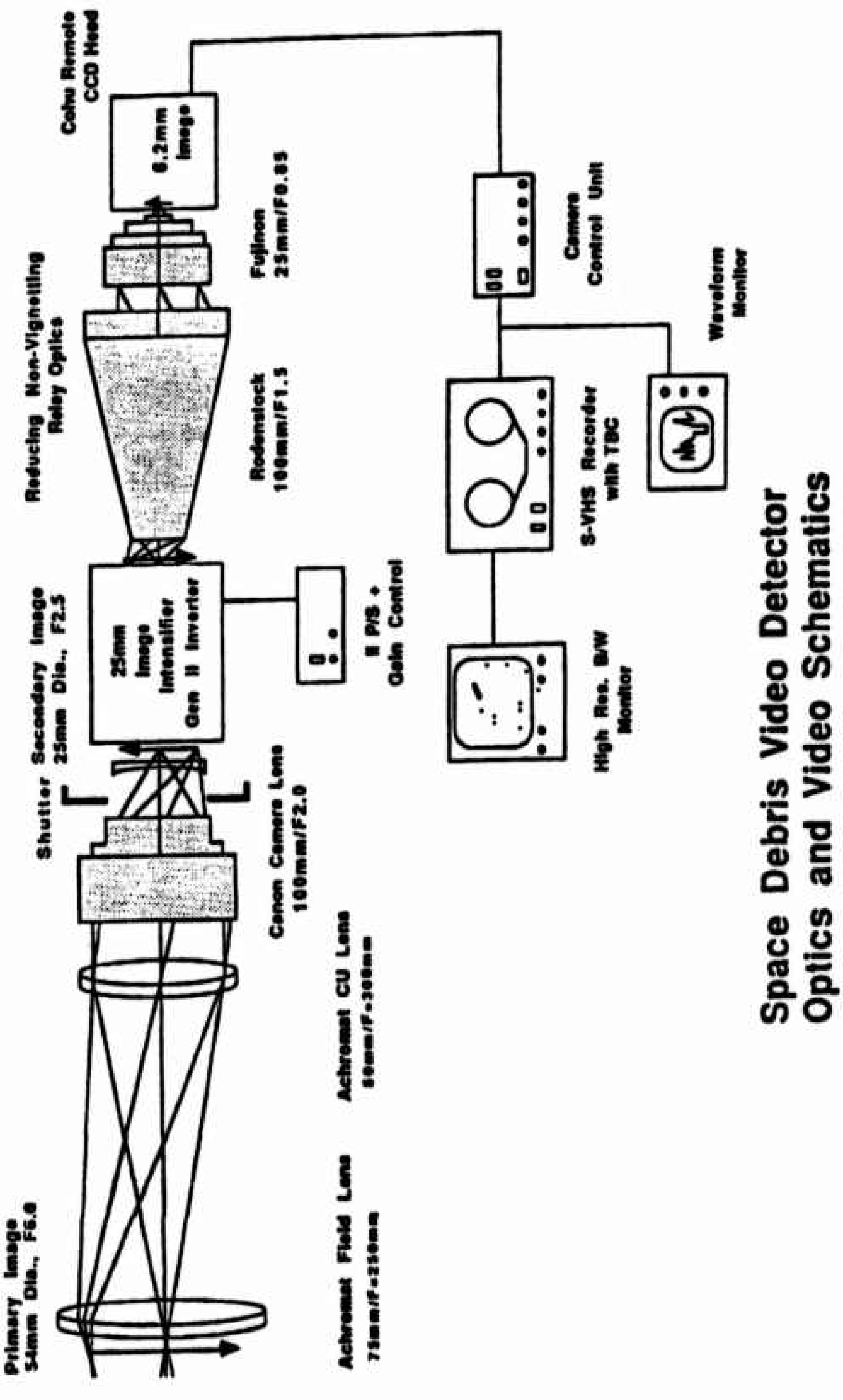

Figure B2. Receiver Schematic for the Wright Patterson
100-inch Collimator for Debris Detection Efforts

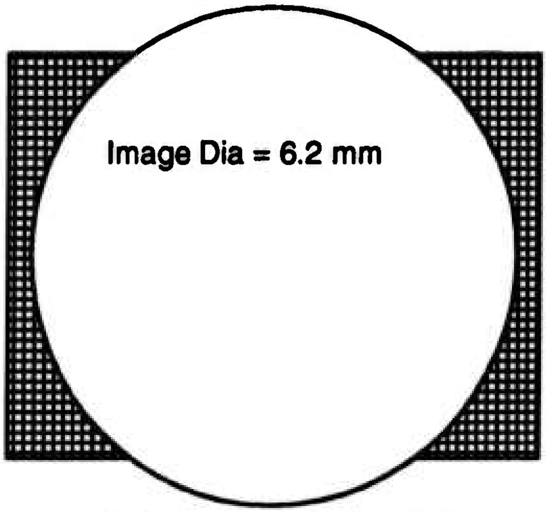

Figure B3. Placement of 0.2 Degree Field of View onto Charge Coupled Device

The image of the debris moves across the CCD and produces a streak. The length of the streak determines the angular velocity and hence the altitude of the object. The intensity of the streak is used to determine the size of the object. The direction of the streak is directly related to the inclination of the object. The faster the image of the object, the larger number of pixels the signal will be spread over and hence the less signal per pixel. The background signal will not change with the speed of the object. For an object moving at 500 km, an approximate angular velocity is 0.87 deg per second. With a 0.2 degree field of view, this means the debris will be in the field of view for only 0.2 seconds. At TV rates of 30 frames per second, 0.2 seconds is only six frames. Objects at a higher altitude will remain in view for a longer period of time.

The effect of spreading the signal over many pixels with a nominal level of background in each will be to decrease the detection capability of the setup. This problem can be overcome by using one of two methods: the first is to steer the telescope at the expected angular velocity of the debris and the second is to electronically shift the pixels on the CCD to create a Time Delay Integration (TDI). Either of these methods limits the detectable objects to those that match the velocity with which the system is driven. However, it allows for concentration of the entire signal on a few pixels instead of spreading it over many pixels, thus allowing for significant gains in minimum detectable size. Mechanical scanning of the 12 story Wright Patterson collimator is not possible. Development of the TDI mode for Wright Patterson facility is currently underway and the modification to the receiver systems will include changing the camera controller and possibly the CCD.

The output of the CCD is read by the camera controller unit by the frame transfer method at TV rates of 30 frames per second. The video output is monitored on a waveform monitor and recorded on a S-VHS format video recorder. This type of commercially available recorder has a resolution of at least 400 TV lines and a signal to noise ratio of 46 or more db. This will provide adequate data storage for post digitizing and processing.

For real-time data monitoring, a high resolution black and white monitor will be be used to give the operator a quick look at the data. A quick manual look at the data will spot larger objects passing through the field of view. For further analysis the data will be digitized and analyzed using computer automated streak detection and image enhancement techniques to be discussed later in this section. All electronic equipment will be installed in an air-transportable, shock-mounted electronics rack to allow for debris measurements at other sites with only minor modifications to the receiver optics. See Figure B4 for a diagram of the electronics rack. Table B1 provides a summary of the specifications for the detector system.

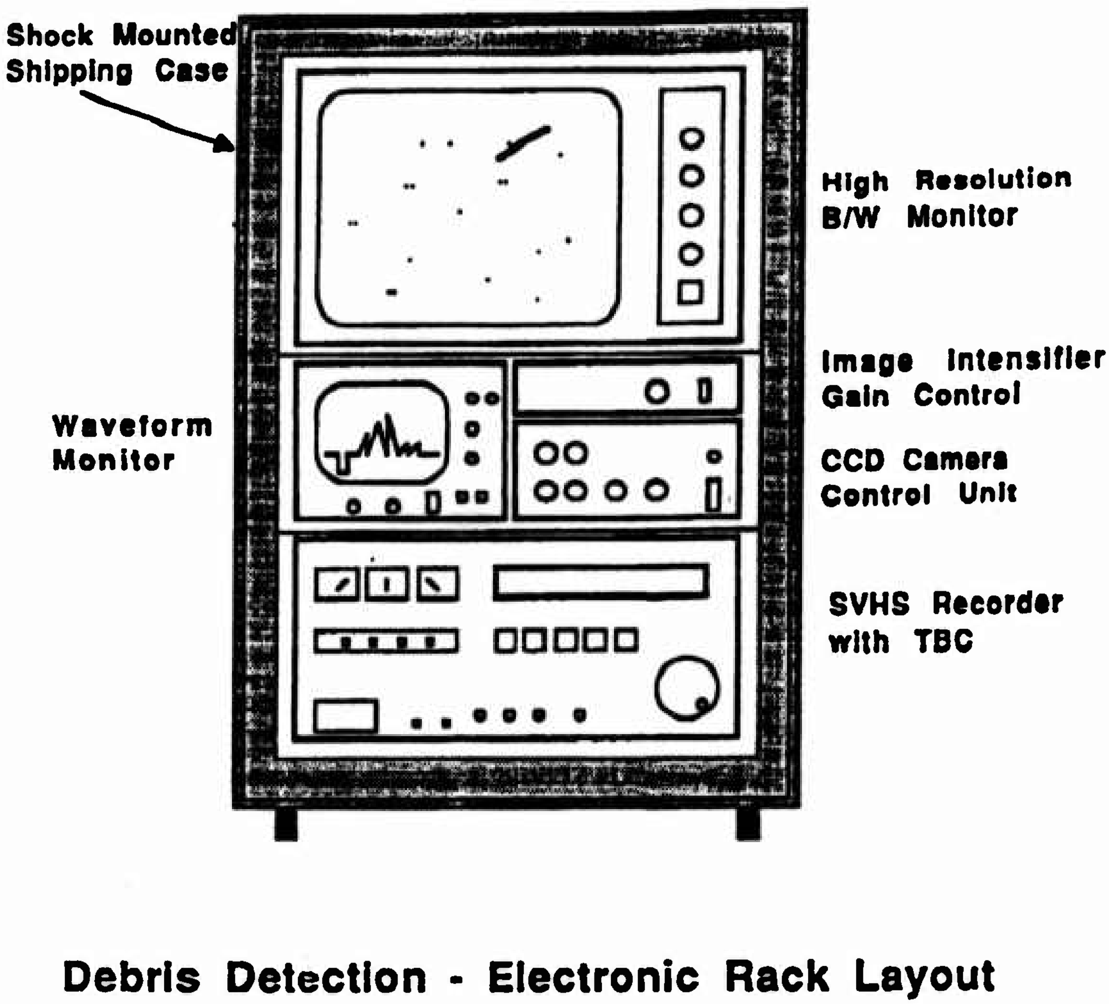

Figure B4. Electronics Rack Layout

Table B1. Specifications for the Phillips Laboratory Wright Patterson 100 inch Detector System

Space Debris Video Detector

System Parameters

1. Telescope:	Diameter	2.54 meter
	Focal Length	15 meter
	F Number	F6.0
	Primary Image Size	60mm (F6.0)
2. Reimaging:	Achromat Field Lens	f = 250mm
	Achromat Close-up Lens	f = 300mm
	Canon Camera Lens	f = 100mm, F2.0
	Field Curvature Correction	f = -xx mm (TBD)
	Image Size at Intensifier	24.5mm (F2.5)
3. Intensifier:	25mm Gen II Inverted Type	
	Gain	55,000 (2854 source)
	Visible Gain	20,000
	Resolution	36+ lp/mm
	Photocathode	S20R
	Phosphor	P20 (10% falltime = 1 msec)
4. Relay Lens:	Non-vignetting lens combination	
	Rodenstock 100mm/F1.5 +	
	Fujinon 25mm/F0.85 (used at F1.4)	
	(can be used at F0.85 with some vignetting)	
	Image Size at CCD	6.2mm
5. Camera:	Cohu CCD	
	Type 6510	frame transfer
		1/2" format, 6.4 x 4.8mm
		Pixels 739 (H) x 484 (V)
	Resolution	H 560 tv lines
		V 350 tv lines
	Sensitivity	Full video 0.4 lux (0db gain)
		Useable 0.01 lux (20db gain)
	S/N	56db
6. Recording:	S-VHS Format	
	Resolution	400+ tv lines
	S/N	46+db

B1 DATA REDUCTION

To date, data reduction has been a tedious process of manually viewing recorded video tapes. The star background moves very slowly and can be removed by subtracting one successive frame from another. This leaves only the objects that move from frame to frame. Debris and satellites are seen as streaks that cross the screen and are detected by carefully viewing the monitor. The sensitivity and consistency of this method is variable. In order to advance the data reduction process, computer-based algorithms are being developed by both the Phillips Laboratory and Lincoln Laboratories to automate the data reduction process and enhance the sensitivity of the data already obtained. These data enhancement techniques will be discussed later in this section.

All future data collected by the sensors participating in the Phillips Laboratory data collection campaign will be analyzed at the Geophysics Directorate. The processing of this data will occur on either a Sun Sparc Station or a Silicon Graphics Work Station. The stored video data will grabbed by a frame grabber and digitized to allow for the digital processing of the data. Some degradation is expected in the recording, storing and retrieval of the data from the video tapes, but analysis of the errors indicates that with the image intensified CCD, the background noise due to the sky background will exceed any noise due to CCD read errors, shot noise, tape storage, and the digital to analog or the analog to digital conversion processes.

The digital processing of the data will allow for significant enhancement of the data over the human based visual method used to date. Methods of shifting and adding sequential frames allows for increases in sensitivity. Computer based data reduction will also provide a systematic approach that will produce the same results each time irrespective of the operator or observer.

B2 SIGNAL DETECTION TECHNIQUES

The video data collected during an optical debris search can be enhanced by processing the video signals in different ways. The minimum detectable size for a given receiver system depends on the type of data collected and the method used for analyzing the data. There are essentially three different methods of detecting debris that need to be considered: single pixel detection, assumed velocity filtering, and pseudo-tracking. Two of these, single pixel detection and assumed velocity, filtering are done during the post-processing of data collected during a staring mode operation of the telescope. Tracking and pseudo-tracking make assumptions about the orbit of the debris and increases the sensitivity to any debris that may be in that particular orbit.

<u>Single Pixel Detection</u>- This is the basic method of detection. A possible detection is identified by the signal level in a single pixel that is above the background noise level. The threshold can be set near the background level because any false detections can be checked by looking at adjacent pixels or additional frames. This method is equally sensitive to all velocities and directions.

<u>Assumed Velocity Filter</u> - This is a post processing technique to enhance the signal levels of objects spread over several pixels or frames. In this method pixels and/or the frames are shifted

and added together. The amount and direction that the pixels or the sequential frames are shifted is dependent upon the velocity that is being analyzed. This allows for the signal from an object on many pixels and many frames to be added together. The noise due to the background signal threshold rises at a slower rate than the signal. Since this is done in post-processing and not during data collection, any and all velocities and directions can be searched, not limiting the number of objects detected to a single assumed velocity. This method is potentially equally sensitive to all velocities and directions, provided that the computer time and power is available to search all velocities.

MIT's Lincoln Laboratories has been developing algorithms for use with its space debris and space based surveillance systems. Output from these algorithms indicate that large increases in sensitivity are practical. Figure B5 shows the output from raw video data. Inside the box is a streak from a space object. Figure B6 is made after subtracting the background and shifting and adding 50 frames by the amount that the object moves during each frame. Note that the object appears significantly brighter and is easier to detect. Figures B7 - B11 show results from shifting and adding the video signal and the potential gains in sensitivity.

Pseudo-Tracking - This method of detection requires a different operation of the receiver/telescope during data collection. Here the signal is concentrated on a single or small number of pixels by scanning the telescope either mechanically by steering the telescope or electronically using Time Delay Integration techniques at an assumed velocity. While the assumed velocity one chooses significantly reduces the number of objects to be seen, the sensitivity increases significantly. The sensitivity to objects with the assumed velocity is increased while the sensitivity of objects with other velocities is reduced.

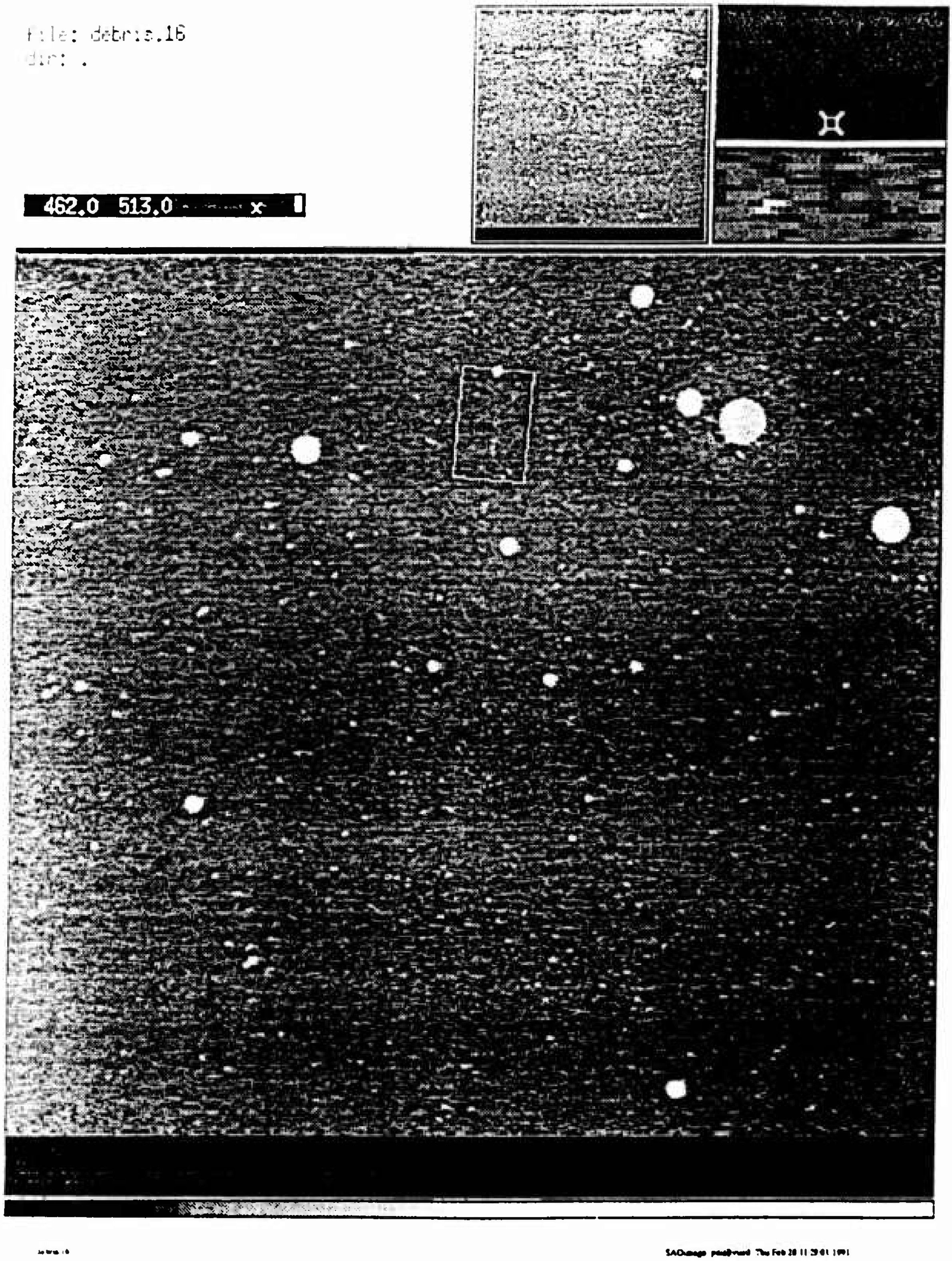

Figure B5. Raw Video Signal of Debris Streak - Single Frame

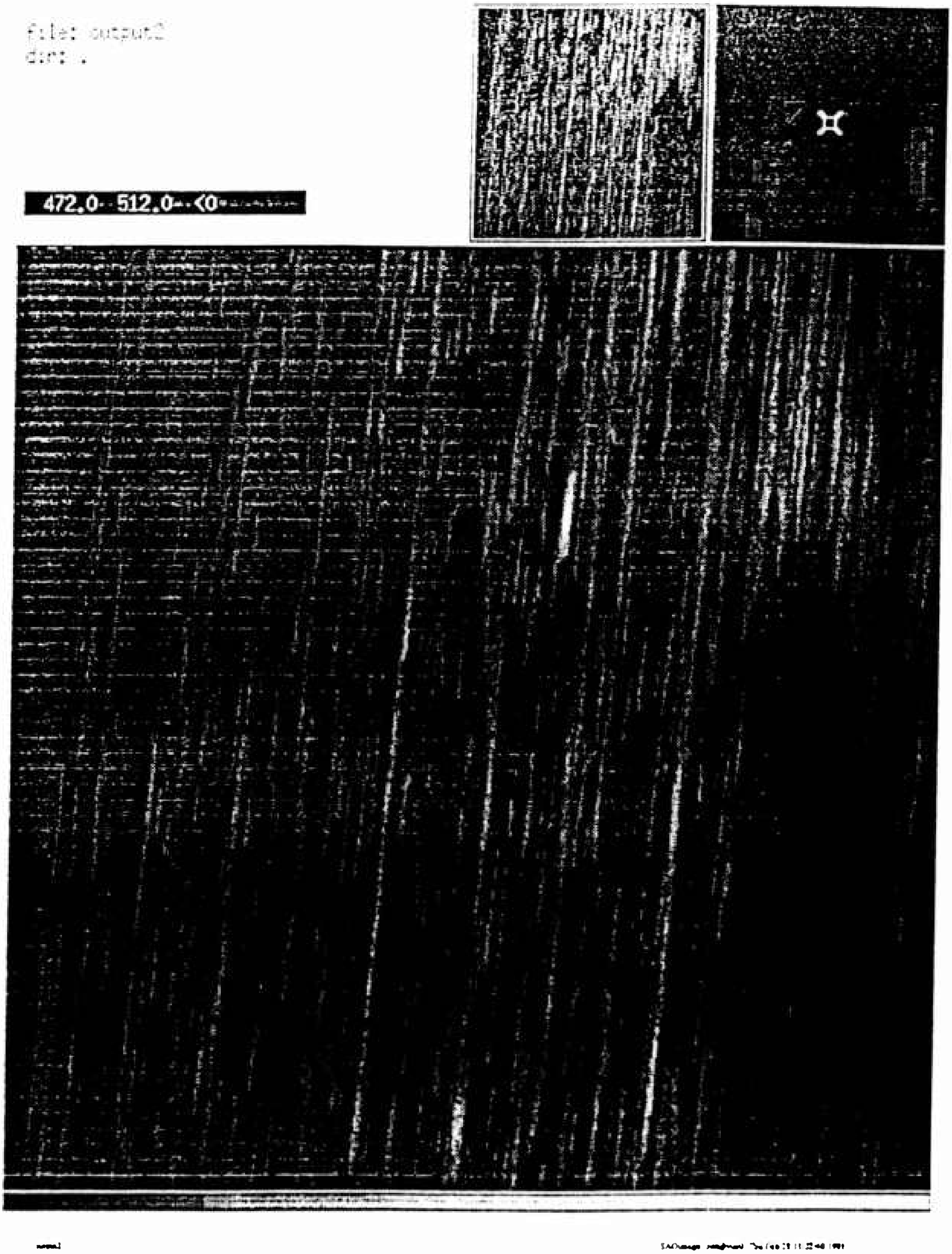

Figure B6. 50 Shifted and Added Video Frames After Background Subtraction of the Same Object as in Figure B5

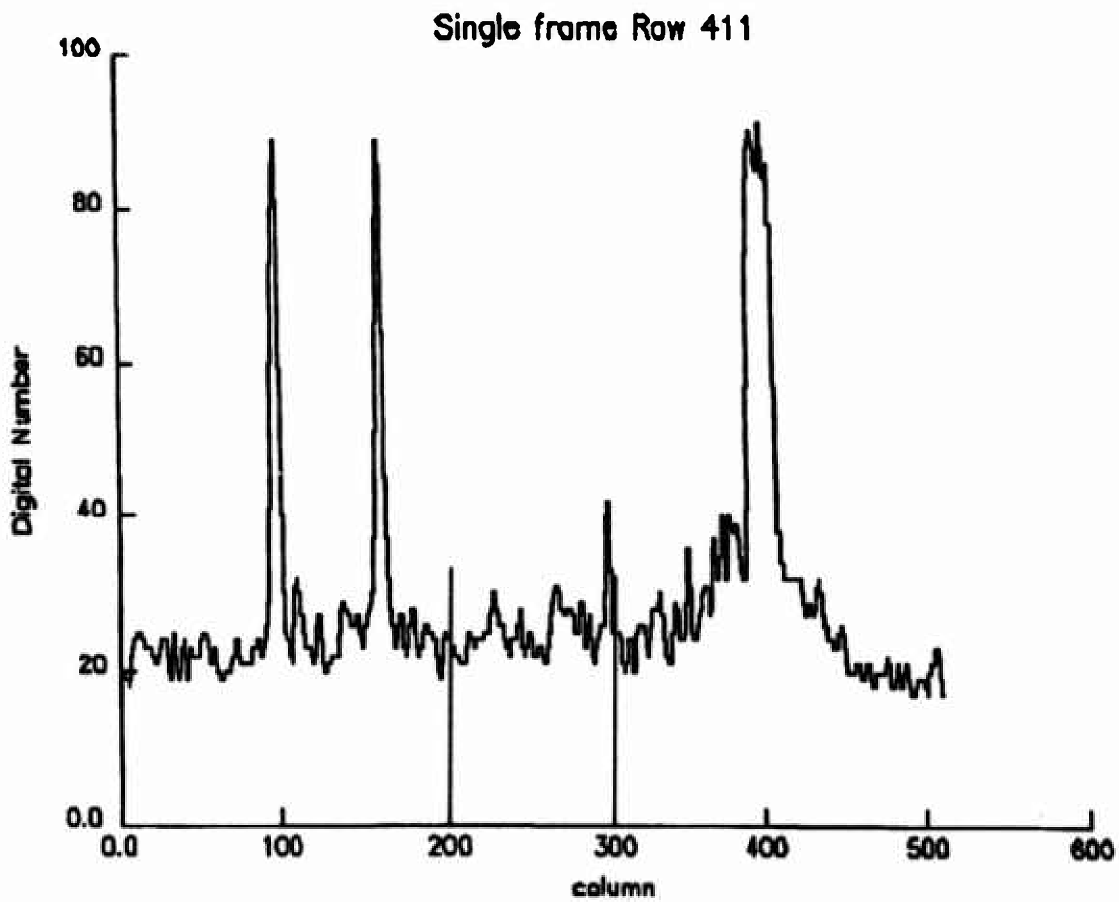

Figure B7. Optical Signal Measured Across a Single Video Frame in the Row in which the Object was Seen. Debris signal between column 200 and 300

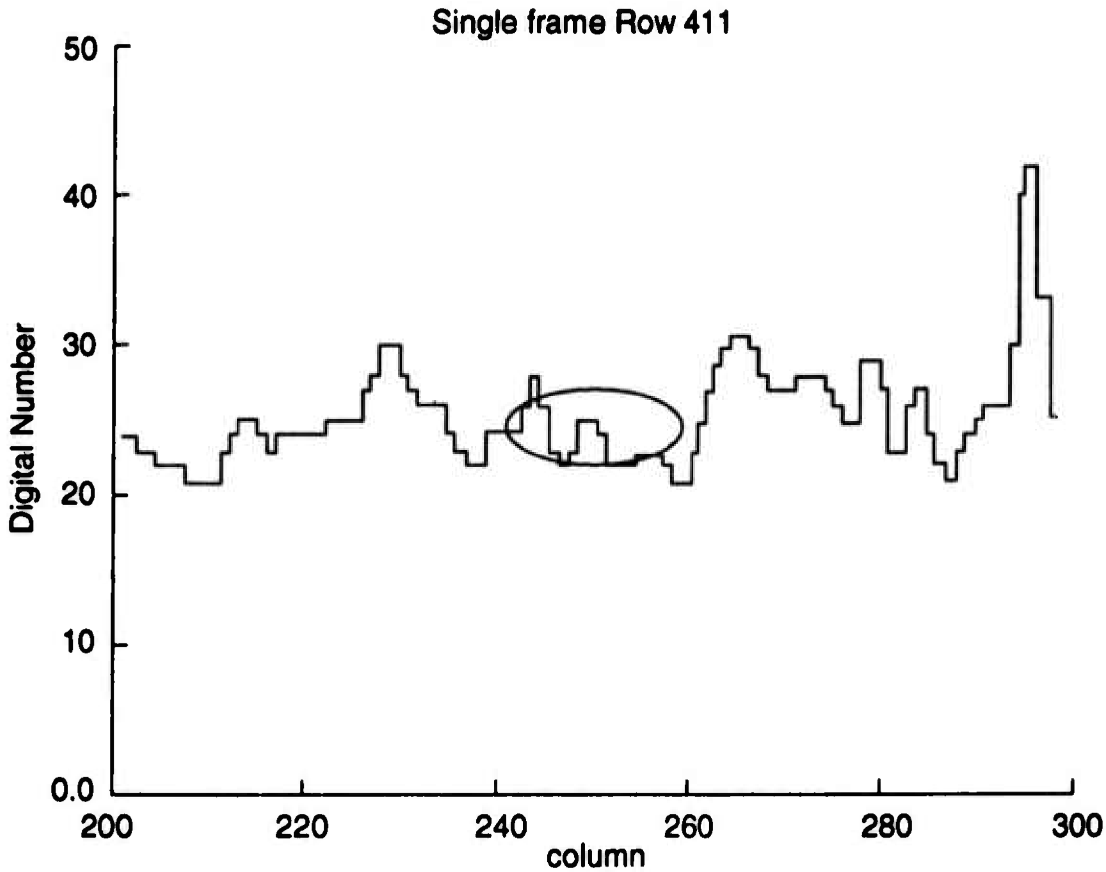

Figure B8. Expanded Optical Signal Measured Across the Frame in the Row in which the object is seen. Debris signal is circled and very hard to distinguish from the background

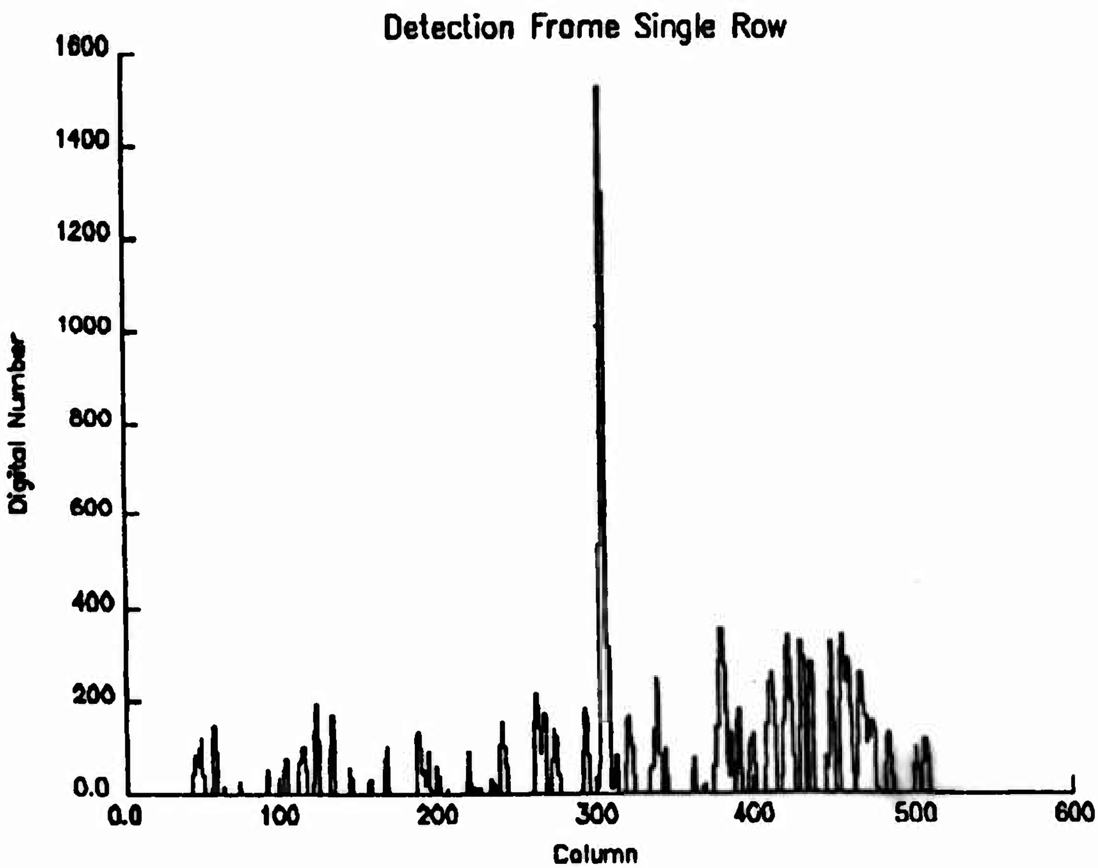

Figure B9. Optical Signal after subtracting the background and applying the assumed velocity filter to 50 frames. Debris signal stands out clearly above background noise. Measured across the video frame

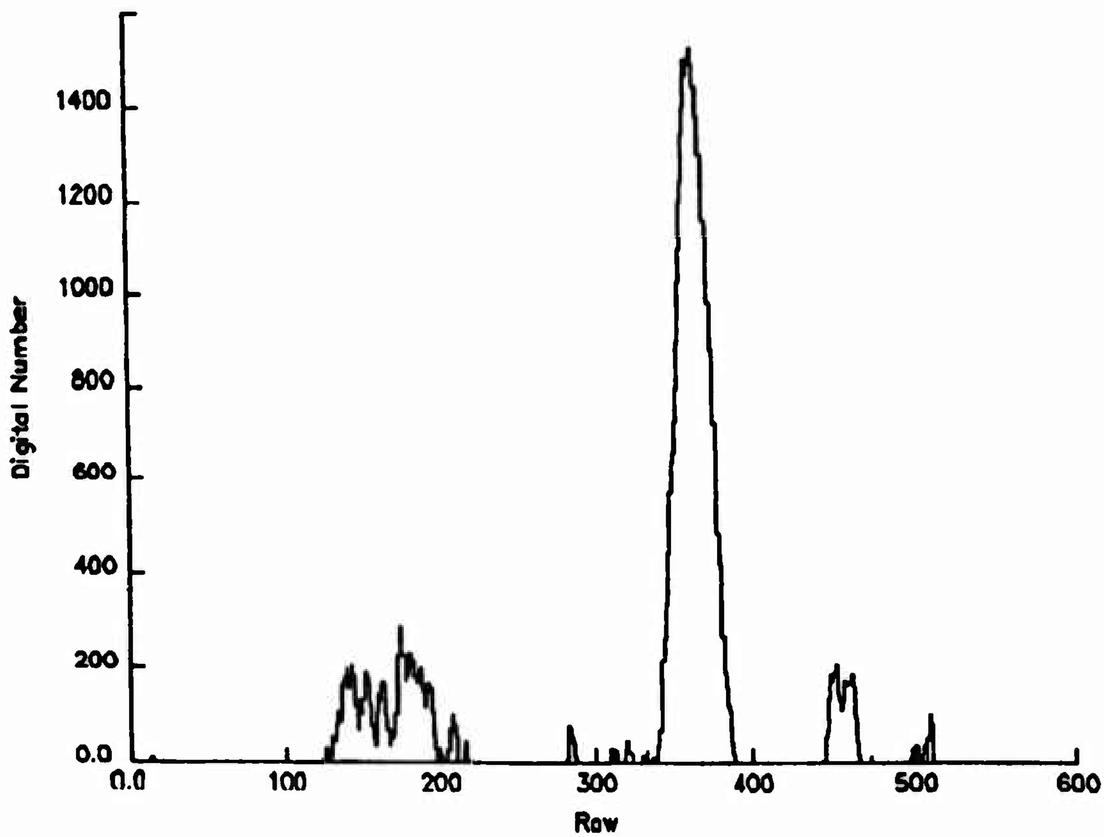

Figure B10. Optical Signal in Column of Debris Optical signal from column of debris after subtracting the background and applying the assumed velocity filter to 50 frames. Debris signal stands out clearly above background noise. (Wider peak is a result of movement of the image during each frame.)

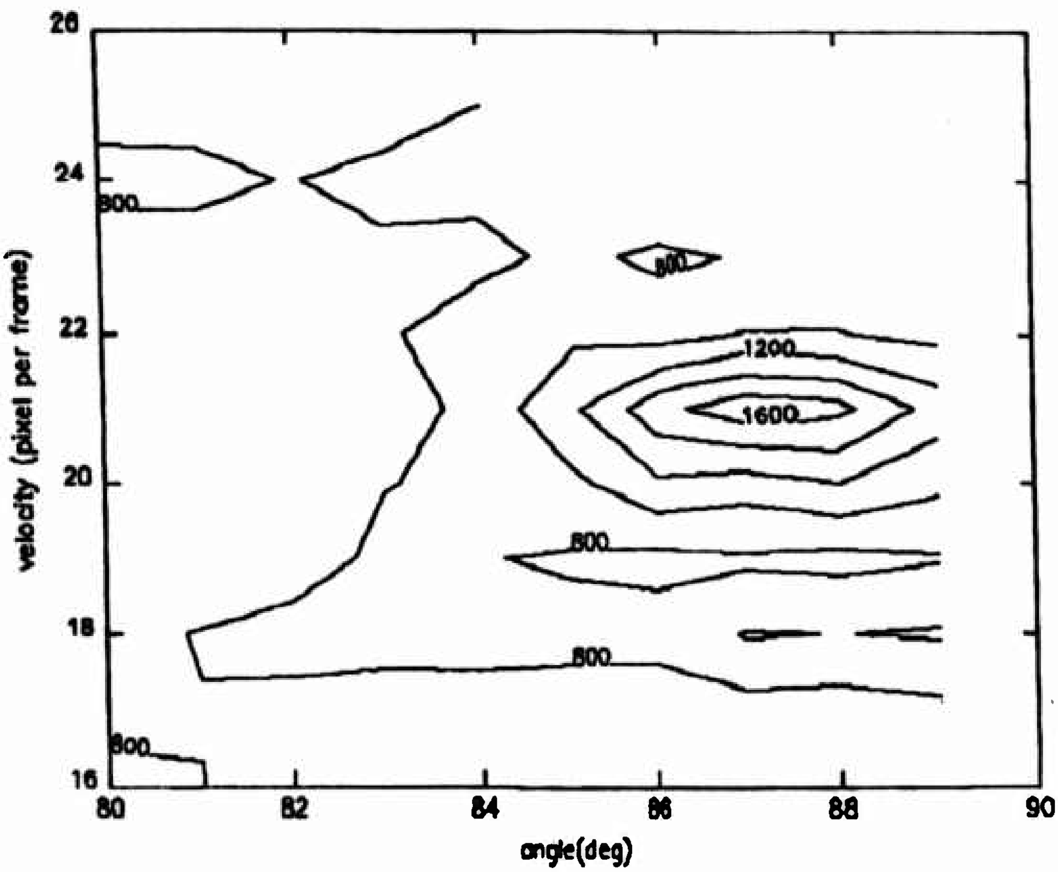

Figure B11. Maximum Optical Signal Obtained for the Debris as a Result of Adding Frames at Different Angles and Velocities. (Contour Value in Digital Number)

Tracking - This requires a telescope that can be driven mechanically or can use a turning mirror to move the field of view at a certain velocity to mechanically maintain the image of the particle on a single pixel as it moves across the sky. The longer the image is tracked the more sensitive the measurement becomes because the signal is integrated during the tracking. This method is not possible for the Wright Patterson effort but is included for demonstration purposes and will be analyzed with the participating sensors.

Each of these different methods has its tradeoff. The single pixel detection method is easily implemented. The assumed velocity filter requires a significant amount of computer resources and time. The pseudo tracking and tracking methods trade the volume of phase space searched for sensitivity and detection capability of smaller objects at the cost of not detecting objects moving in other directions. In order to determine which methods are desirable an analysis of the detection capabilities is in order.

B3 MINIMUM DETECTABLE OBJECT BRIGHTNESS

The minimum detectable size for space debris is a function of many variables. Some variables are location dependent, some are due to atmospheric conditions and some are due to the optical system used to make the detections. To determine the minimum detectable size we will first determine the faintest detectable object. To accomplish this we must determine what the signal and the background noise levels are for the various detection methods.

The derivations of minimum detectable size will use optical magnitudes. Optical magnitudes are a measure of relative brightness of objects started in ancient Greece. Because the originator Hipparchus used a scale of one to six to classify the visible stars which represent approximately a range of 100 in optical signal, each optical magnitude represents a factor of the fifth root of 100 or 2.512.

Visual Magnitude Definitions

By definition, the integrated flux of ($m_v = 0$) star is

$$\int \text{Flux } (m_v = 0)\, d\lambda = 2.5 \times 10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1}$$

Where:

m_v = visual magnitude

λ = wavelength

In the visible region the approximation

$$\text{Flux } (m_v = 0) \approx 3.7 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1} \text{Å}^{-1}$$

holds. For wavelengths near 550 nm with the photon energy near 3.7×10^{12} ergs, one is left with a remarkably easy relationship:

$$\text{Flux}\ (m_v = 0) \approx 1000 \ \text{photons cm}^{-2}\,\text{s}^{-1}\,\text{Å}^{-1}$$

To convert from ($m_v = 0$) to another ($m_v \neq 0$) use:

$$\text{Flux}\ (m_v = 0) = 2.512^{-m_v} \times \text{Flux}\ (m_v = 0)$$

Photon fluxes received by a telescope and optical brightness are related by:

$$S_{frame} = 1000 \cdot 2.512^{-OB} \cdot A_{tel} \cdot e_t \cdot BW \cdot e_d \cdot \tau$$

$$S_{frame} = 7.853 \times 10^6 \cdot 2.512^{-OB} \cdot D_{tel}^2 \cdot e_t \cdot BW \cdot e_d \cdot \tau$$

where:

S = Signal from the debris in number of photons
OB = Object Brightness in optical magnitudes
A_{tel} = Collection area of the telescope in cm^2
D_{tel} = Diameter of the telescope in meters
e_t = Efficiency of the telescope and detector optics
BW = Bandwidth that the detector is sensitive in angstroms
e_d = Efficiency of the detector over the bandwidth
τ = integration time per frame in seconds

The factor of 7,853 that appears in the second equation is a conversion factor from area in square centimeters to diameter in square meters. The results of the minimum detectable object brightness calculations will be given in optical magnitude.

B3.1 Single Pixel Detection

Single Pixel Detection relies on the signal contained in a single pixel and the average background signal. In order to be detected the signal divided by the background noise must be larger than the minimum signal to noise ratio.

B3.1.1 DEBRIS OPTICAL SIGNAL STRENGTH

The optical signal per frame from debris is given by the equation

$$S_{frame} = 7.853\times10^{6}\cdot 2.512^{-OB}\cdot D_{tel}^{2}\cdot e_{t}\cdot B\,W\cdot e_{d}\cdot \tau$$

where the variables are the same as above.

Because the object is moving at a relatively high angular velocity the image will be spread over a number of pixels in each frame. The number of pixels per frame the object signal is spread across is found by

$$N_{pixels/frame} = \frac{AV\cdot\tau}{FOV} N_{across\ detector}$$

where:

AV = Angular velocity in degrees per second
FOV = Full field of view in degrees
τ = integration time per frame in seconds
N = Number of pixels across the detector

B3.1.2 ANGULAR VELOCITY FROM THE OBSERVING SITE

For a circular orbit, the angular velocity with respect to the receiver site is found by using the mean motion of a satellite.

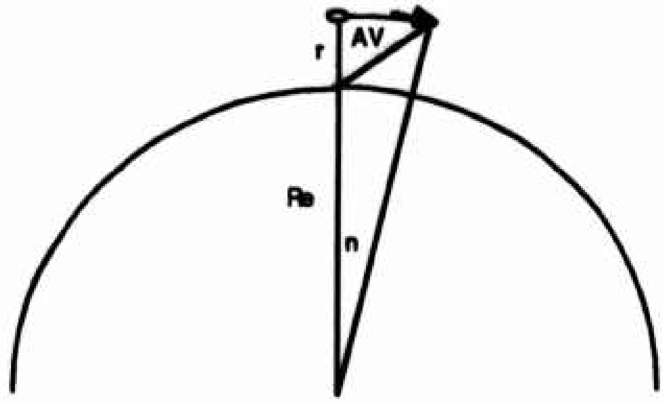

Figure B12. Diagram of Angular Velocity With Respect to the Observing Site
n = mean motion of the satellite

The mean motion of angular velocity from the center of the Earth of a satellite is found for an object as shown in Figure B12 by:

$$n = \left(\frac{\mu}{(r+R_e)^3}\right)^{0.5}$$

where

n = mean motion of a satellite in radians per second
r = Height above the Earth's surface in kilometers,
R_e = Radius of the Earth = 6,378 km
μ = Gravitation constant × mass of the Earth = 3.98×10^5 km^3/sec^2

The apparent angular velocity as seen from the observation site for angles near vertical can be approximated by:

$$AV = \frac{180}{\pi} \cdot \arctan\left[\frac{(r+R_e) \cdot \left(\frac{\mu}{(r+R_e)^3}\right)^{0.5}}{r}\right]$$

where:

AV = Apparent angular velocity in degrees per second

The number of pixels included in the streak is important for two reasons: first, because it determines the number of pixels that the signal from the debris will be spread over; and second, it determines the number of pixels from which the background will be included. At Wright Patterson, the relationship between angular velocity and the streak length in pixels is defined by the time per frame, the field of view, the image size at the detector and the pixel size as shown below.

Number of Pixels =AV (deg /sec) × 0.033 sec / 0.2 deg × 600 pixels per side Table B2 shows the number of pixels per frame for different altitudes for the Wright Patterson configuration.

Table B2. Number of Pixels per Frame for Different Altitudes at Wright Patterson

Range (km)	Angular Velocity	Number of Pixels
200	2.225	220.2
300	1.471	145.6
400	1.094	108.3
500	0.868	85.9
600	0.718	71.0
700	0.610	60.4
800	0.530	52.4
900	0.467	46.2
1000	0.417	41.3
1500	0.268	26.5
2000	0.193	19.1
2500	0.149	14.8
3000	0.120	11.9
4000	0.085	8.4
5000	0.064	6.3
6000	0.050	5.0
7000	0.041	4.0
8000	0.034	3.3
10000	0.024	2.4
12000	0.018	1.8
14000	0.014	1.4
16000	0.011	1.1
18000	0.009	0.9
20000	0.007	0.7

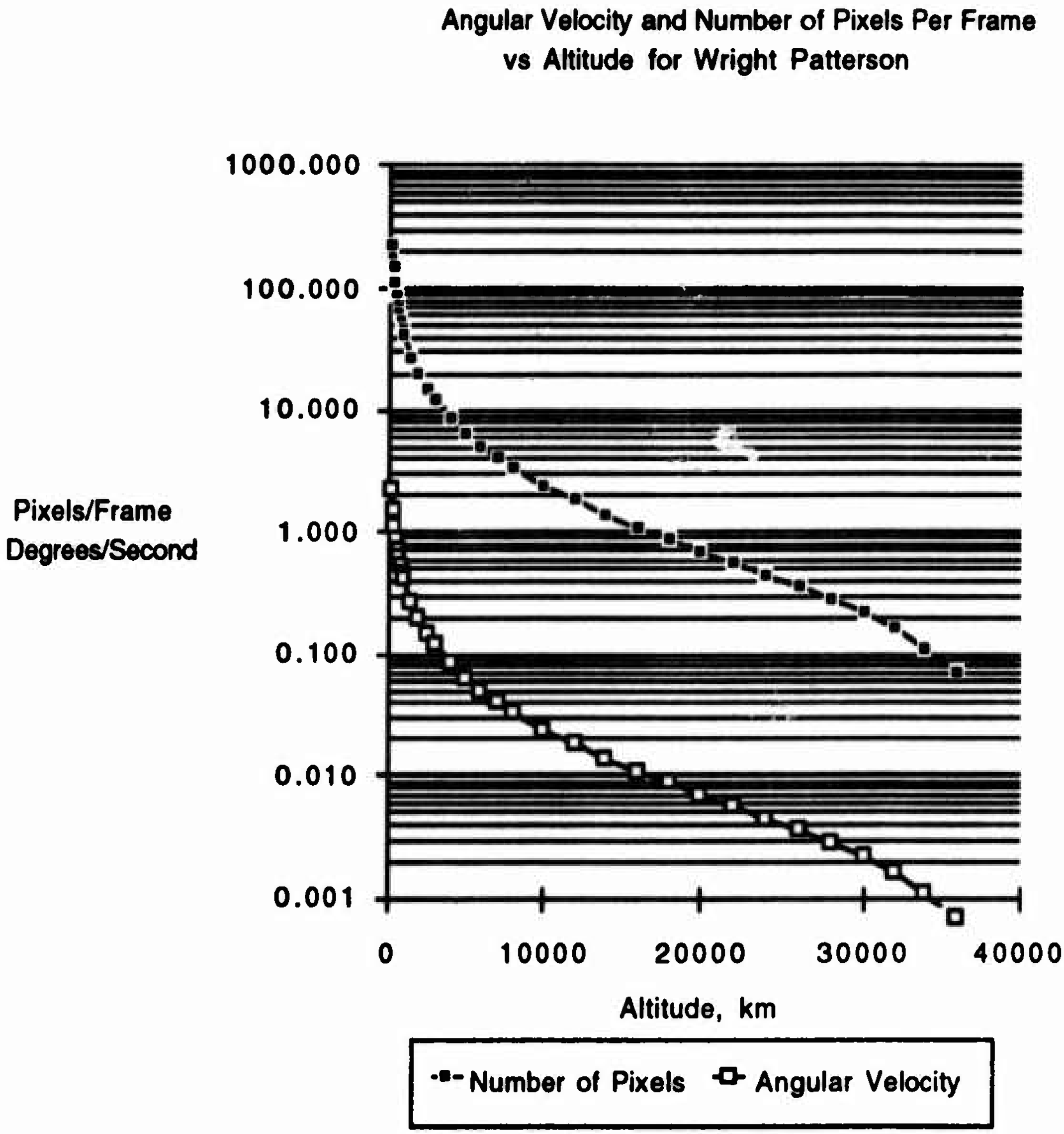

Figure B13. Angular Velocity and Number of Pixels per Frame
vs Altitude for Wright Patterson

At Wright Patterson a signal from an object at 500 km will be spread across approximately 85 pixels per frame. The object will only be in a certain pixel for 0.00039 second (frame time/number of pixels) and the background will be integrating in all pixels for the duration of the frame time.

Dividing the signal per frame by the number of pixels to find the signal per pixel, we find that:

$$S_{Pixel} = \frac{S_{frame}}{N_{pixels/frame}} = \frac{7.853X10^6 \cdot 2.512^{-OB} \cdot D_{tel}^2 \cdot e_t \cdot BW \cdot e_d \cdot \tau}{\frac{AV \cdot \tau}{FOV} \cdot N_{across\ detector}}$$

$$S_{Pixel} = \frac{S_{frame}}{N_{pixels/frame}} = \frac{7.853X10^6 \cdot 2.512^{-OB} \cdot D_{tel}^2 \cdot e_t \cdot BW \cdot e_d \cdot FOV}{AV \cdot N_{across\ detector}}$$

The background signal per frame is a function of the brightness of the sky, the area of the telescope, the efficiency of the system and the integration time per frame.

$$NSB_{frame} = 1000 \times 2.512^{-NSB} \cdot A_{tel} \cdot e_t \cdot BW \cdot e_d \cdot \tau \cdot FOV_{arcsec^2}$$

$$NSB_{frame} = 7.853 \times 10^6 \cdot 2.512^{-NSB} \cdot D_{tel}^2 \cdot e_t \cdot BW \cdot e_d \cdot \tau \cdot 1.296 \times 10^7 FOV_{deg}^2$$

$$NSB_{frame} = 1.0178 \times 10^{14} \cdot 2.512^{-NSB} \cdot D_{tel}^2 \cdot e_t \cdot BW \cdot e_d \cdot \tau \cdot FOV_{deg}^2$$

Where in addition to those terms previously explained:

NSB = Night sky background in optical magnitudes
FOV_{arcsec^2} = Field of view in arcseconds
FOV Degrees = Field of view in degrees from edge to edge

The factor of 7,853 is again due to converting from area in square centimeters to telescope diameter in meters. The factor of 1.296×10^7, which is 3600 squared, is a result of converting field of view from the arcseconds squared to degrees.

The background signal per pixel is found by dividing the the amount of background signal by the number of pixels:

$$NSB_{pixel} = \frac{NSB_{frame}}{N_{Pixels\ in\ detector}} = \frac{1.0178 \times 10^{14} \cdot 2.512^{-NSB} \cdot D_{tel}^2 \cdot e_t \cdot BW \cdot e_d \cdot \tau \cdot FOV_{deg}^2}{N_{Pixels\ in\ detector}}$$

where N pixels in detector is equal to the number of pixels in the detector. This is assumed to be the square of the number of pixels across the detector because of the uncertainty of the orientation of the detector to the debris streak.

The Background Statistical Noise per pixel is the square root of the background signal because of Poissons statistics of counting events (photon arrivals) with a random time of occurrence. The background noise per pixel is found by:

$$S_{Noise} = \sqrt{NSB_{pixel}} = \frac{1.0089\times10^{7}\cdot 2.512^{\frac{NSB}{2}}\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot \tau^{.5}\cdot FOV_{deg}}{N^{.5}_{Pixels\ in\ detector}}$$

To make a detection based on a single pixel the signal to noise ratio must be above a detectable threshold.

$$\frac{S_{Pixel}}{S_{Noise}} > SNR$$

$$\frac{S_{Pixel}}{S_{Noise}} = \frac{\dfrac{7.853\times10^{6}\cdot 2.512^{-OB}\cdot D^2_{tel}\cdot e_t\cdot BW\cdot e_d\cdot FOV}{AV\cdot N_{across\ detector}}}{\dfrac{1.0089\times10^{7}\cdot 2.512^{\frac{NSB}{2}}\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot \tau^{.5}\cdot FOV_{deg}}{N^{.5}_{Pixels\ in\ detector}}} > SNR$$

By rearranging and simplifying we find that

$$\frac{S_{Pixel}}{S_{Noise}} = \frac{0.7784\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot 2.512^{\frac{NSB}{2}}}{2.512^{OB}\cdot \tau^{.5}\cdot AV} > SNR$$

$$2.512^{OB} = \frac{0.7784\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot 2.512^{\frac{NSB}{2}}}{\tau^{.5}\cdot AV\cdot SNR}$$

Taking log(2.512) we arrive at a simple expression for the minimum detectable optical brightness of an object using the single pixel detection method:

$$OB = -0.2720 + \frac{NSB}{2} + 2.5 \cdot LOG(D_{Tel}) + 1.25 \cdot LOG(e_t) + 1.25 \cdot LOG(BW) + 1.25 \cdot LOG(e_d) - 1.25 \cdot LOG(\tau) - 2.5 \cdot LOG(AV) - 2.5 \cdot LOG(SNR)$$

For the optical brightness of an object at the surface of the Earth, an atmospheric extinction coefficient (e) and an appropriate measure of the air mass (X) needs to be included to account for atmospheric losses. The equation for minimum detectable size including these terms is:

$$OB = -0.2720 + \frac{NSB}{2} + 2.5 \cdot LOG(D_{Tel}) + 1.25 \cdot LOG(e_t) + 1.25 \cdot LOG(BW) + 1.25 \cdot LOG(e_d) - 1.25 \cdot LOG(\tau) - 2.5 \cdot LOG(AV) - 2.5 \cdot LOG(SNR) - eX$$

B3.2 Assumed Velocity Filtering (frames only)

By shifting sequential frames a specified number of pixels in a direction that corresponds to an assumed velocity and adding , it is possible to significantly enhance the signal per pixel at a rate faster than the noise signal. The signal per pixel per frame is the same as in single pixel detection.

$$S_{Pixel_{frame}} = \frac{S_{frame}}{N_{pixels/frame}} = \frac{7.853 \times 10^6 \cdot 2.512^{-OB} \cdot D_{tel}^2 \cdot e_t \cdot BW \cdot e_d \cdot FOV}{AV \cdot N_{across\ detector}}$$

By shifting and adding it is possible to add all the streaks in different frames together to detect the object. The number of frames required to do this is determined by the angular velocity of the object, the field of view of the telescope and the time per frame:

$$S_{Pixel} = S_{Pixel_{frame}} \cdot N_{frames} = \frac{7.853 \times 10^6 \cdot 2.512^{-OB} \cdot D_{tel}^2 \cdot e_t \cdot BW \cdot e_d \cdot FOV}{AV \cdot N_{across\ detector}} \cdot \frac{FOV}{AV \cdot \tau}$$

Hence the amount of signal available per pixel is

$$S_{Pixel} = \frac{7.853 \times 10^6 \cdot 2.512^{-OB} \cdot D_{tel}^2 \cdot e_t \cdot BW \cdot e_d \cdot FOV^2}{AV^2 \cdot N_{across\ detector} \cdot \tau}$$

By shifting and adding the frames you also increase the background noise. The background signal per pixel per frame is the same as before:

$$NSB_{pixel_{frame}} = \frac{NSB_{frame}}{N_{Pixels\ in\ detector}} = \frac{1.0178\times10^{14}\cdot2.512^{-NSB}\cdot D_{tel}^2\cdot e_t\cdot BW\cdot e_d\cdot\tau\cdot FOV_{deg}^2}{N_{Pixels\ in\ detector}}$$

The background signal is increased by the the number of frames added together.

$$NSB_{pixel} = NSB_{pixel_{frame}}\cdot N_{frames} = \frac{1.0178\times10^{14}\cdot2.512^{-NSB}\cdot D_{tel}^2\cdot e_t\cdot BW * e_d\cdot\tau\cdot FOV_{deg}^2}{N_{Pixels\ in\ detector}}\ \frac{FOV}{AV\cdot\tau}$$

Simplifying, we see that

$$NSB_{pixel} = \frac{1.0178\times10^{14}\cdot2.512^{-NSB}\cdot D_{tel}^2\cdot e_t\cdot BW\cdot e_d\cdot FOV_{deg}^3}{N_{Pixels\ in\ detector}\cdot AV}$$

Once again, the background noise is the square root of the background signal

$$S_{Noise} = \sqrt{NSB_{pixel}} = \frac{1.0089\times10^{7}\cdot2.512^{-\frac{NSB}{2}}\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot FOV_{deg}^{1.5}}{N_{Pixels\ in\ detector}^{.5}\cdot AV^{.5}}$$

Again setting the required signal divided by the noise to the required signal to noise ratio equates to

$$\frac{S_{Pixel}}{S_{Noise}} = \frac{\dfrac{7.853\times10^{6}\cdot2.512^{-OB}\cdot D_{tel}^{2}\cdot e_t\cdot BW\cdot e_d\cdot FOV^{2}}{AV^{2}\cdot N_{across\ detector}\cdot\tau}}{\dfrac{1.0089\times10^{7}\cdot2.512^{\frac{NSB}{2}}\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot FOV_{deg}^{1.5}}{N_{Pixels\ in\ detector}^{.5}\cdot AV^{.5}}} > SNR$$

which simplifies to

$$\frac{S_{Pixel}}{S_{Noise}} = \frac{0.7784\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot 2.512^{\frac{NSB}{2}}\cdot FOV^{.5}}{2.512^{OB}\cdot\tau\cdot AV^{1.5}} > SNR$$

$$2.512^{OB} = \frac{0.7784\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot 2.512^{\frac{NSB}{2}}\cdot FOV^{.5}}{\tau\cdot AV^{1.5}\cdot SNR}$$

Again by taking the log base 2.512 we arrive at a simple equation for the minimum detectable optical brightness for an assumed velocity filter that shifts only the frames.

$$OB = -0.2720 + \frac{NSB}{2} + 2.5\cdot LOG(D_{Tel}) + 1.25\cdot LOG(e_t) + 1.25\cdot LOG(BW)$$
$$+ 1.25\cdot LOG(e_d) + 1.25\cdot log(FOV) - 2.5\cdot LOG(\tau) - 3.75\cdot LOG(AV) - 2.5\cdot OG(SNR)$$

By including the atmospheric extinction term described earlier we arrive at

$$OB = -0.2720 + \frac{NSB}{2} + 2.5\cdot LOG(D_{Tel}) + 1.25\cdot LOG(e_t) + 1.25\cdot LOG(BW)$$
$$+ 1.25\cdot LOG(e_d) + 1.25\cdot log(FOV) - 2.5\cdot LOG(\tau) - 3.75\cdot LOG(AV) - 2.5\cdot LOG(SNR) - eX$$

B3.3 Assumed Velocity Filtering (Single Frame)

Another method for utilizing the idea of the assumed velocity filtering is to shift and add the pixels in a specific frame in certain directions corresponding with an assumed velocity. The signal available by this method is the sum of all pixels with signals, which is simply the signal per frame found earlier:

$$S_{frame} = 7.853\times10^{6}\cdot2.512^{-OB}\cdot D_{tel}^{2}\cdot e_t\cdot BW\cdot e_d\cdot\tau$$

The background signal per pixel is also the same as we previously found:

$$NSB_{pixel_{frame}} = \frac{NSB_{frame}}{N_{Pixels\ in\ detector}} = \frac{1.0178\times10^{14}\cdot2.512^{-NSB}\cdot D_{tel}^{2}\cdot e_t\cdot BW\cdot e_d\cdot\tau\cdot FOV_{deg}^{2}}{N_{Pixels\ in\ detector}}$$

The background signal after adding the pixels in a certain direction is just the total background signals in the summed pixels:

$$NSB_{Streak_{frame}} = NSB_{pixel_{frame}}\cdot N_{pixels\ in\ streak}$$

$$NSB_{Streak_{frame}} = \frac{1.0178\times10^{14}\cdot2.512^{-NSB}\cdot D_{tel}^{2}\cdot e_t\cdot BW\cdot e_d\cdot\tau\cdot FOV_{deg}^{2}}{N_{Pixels\ in\ detector}}\ \frac{AV\cdot\tau\cdot N_{across\ detector}}{FOV}$$

$$NSB_{Streak_{frame}} = \frac{1.0178\times10^{14}\cdot2.512^{-NSB}\cdot D_{tel}^{2}\cdot e_t\cdot BW\cdot e_d\cdot\tau^{2}\cdot FOV_{deg}\cdot AV}{N_{across\ detector}}$$

The background noise is again found by taking the square root of the NSB above:

$$S_{Noise} = \frac{1.0089\times10^{7}N_{across\ detector}^{.5}\cdot\ 2.512^{-\frac{NSB}{2}}N_{across\ detector}^{.5}\cdot\ D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot\tau\cdot FOV_{deg}^{.5}\cdot AV^{.5}}{N_{across\ detector}^{.5}}$$

Again, setting the signal over the noise equal to the required signal to noise ratio we get:

$$\frac{S_{Pixel}}{S_{Noise}} = \frac{7.853X10^{6}\cdot 2.512^{-OB}\cdot D_{tel}^{2}\cdot e_t\cdot BW\cdot e_d\cdot \tau}{\dfrac{1.0089\times 10^{7}\cdot 2.512^{\frac{NSB}{2}}\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot \tau\cdot FOV_{deg}^{.5}\cdot AV^{.5}}{N_{across\ detector}^{.5}}} > SNR$$

This simplifies to

$$\frac{S_{Pixel}}{S_{Noise}} = \frac{0.7784\cdot 2.512^{\frac{NSB}{2}}\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot N_{across\ detector}^{.5}}{2.512^{OB}\cdot FOV_{deg}^{.5}\cdot AV^{.5}} > SNR$$

$$2.512^{OB} = \frac{0.7784\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot 2.512^{\frac{NSB}{2}}\cdot N_{across\ detector}^{.5}}{AV^{.5}\cdot FOV^{.5}\cdot SNR}$$

This gives us simple equation for the minimum detectable object utilizing an assumed velocity filter on a single frame:

$$OB = -0.2720 + \frac{NSB}{2} + 2.5\cdot LOG(D_{Tel}) + 1.25\cdot LOG(e_t) + 1.25\cdot LOG(BW) + 1.25\cdot \log(N_{across\ detector}) + 1.25\cdot LOG(e_d) - 1.25\cdot \log(FOV) - 1.25\cdot LOG(AV) - 2.5\cdot LOG(SNR)$$

By including the atmospheric extinction term described earlier we get:

$$OB = -0.2720 + \frac{NSB}{2} + 2.5\cdot LOG(D_{Tel}) + 1.25\cdot LOG(e_t) + 1.25\cdot LOG(BW) + 1.25\cdot \log(N_{across\ detector}) + 1.25\cdot LOG(e_d) - 1.25\cdot \log(FOV) - 1.25\cdot LOG(AV) - 2.5\cdot LOG(SNR) - eX$$

B3.4 Assumed Velocity Filter (Streak Compression and Multiple Frames)

By combining both the signal in the streak within a frame and the signal contained in multiple frames it is possible to maximize the signal used to detect the object while utilizing the staring mode of operation.

Here the signal included in the streak in each frame is

$$S_{frame} = 7.853\times10^{6}\cdot2.512^{-OB}\cdot\ D^2_{tel}\cdot e_t\cdot BW\cdot e_d\cdot\tau$$

Multiplying this by the number of frames in which the streak will appear gives the total available signal:

$$S_{total} = S_{frame}\cdot N_{frames} = 7.853\times10^{6}\cdot2.512^{-OB}\cdot\ D^2_{tel}\cdot e_t\cdot BW\cdot e_d\cdot\tau\cdot\frac{FOV}{AV\cdot\tau}$$

$$S_{total} = \frac{7.853\times10^{6}\cdot2.512^{-OB}\cdot\ D^2_{tel}\cdot e_t\cdot BW\cdot e_d\cdot FOV}{AV}$$

The background is also increased by the background signal per pixel times the total number of pixels summed.

$$NSB_{pixel} = NSB_{pixel_{frame}}\cdot N_{frames}\cdot N_{pixels_{Streak}}$$

$$NSB_{pixel} = \frac{1.0178X10^{14}\cdot2.512^{-NSB}\cdot\ D^2_{tel}\cdot e_t\cdot BW\cdot e_d\cdot\tau\cdot FOV^2_{deg}}{N_{Pixels\ in\ detector}}\ \frac{FOV}{AV*\tau}\ \frac{AV\cdot\tau\cdot N_{across\ detector}}{FOV}$$

$$NSB_{pixel} = \frac{1.0178\times10^{14}\cdot2.512^{-NSB}\cdot\ D^2_{tel}\cdot e_t\cdot BW\cdot e_d\cdot\tau\cdot FOV^2_{deg}}{N_{across\ detector}}$$

The background noise is

$$S_{Noise} = \sqrt{NSB} = \frac{1.0089\times10^{7}\cdot 2.512^{\frac{NSB}{2}}\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot \tau^{.5}\cdot FOV_{deg}}{N_{across\ detector}^{.5}}$$

Dividing the signal by the noise gives

$$\frac{S_{Pixel}}{S_{Noise}} = \frac{\dfrac{7.853\times10^{6}\cdot 2.512^{-OB}\cdot D_{tel}^{2}\cdot e_t\cdot BW\cdot e_d\cdot FOV}{AV}}{\dfrac{1.0089X10^{7}\cdot 2.512^{\frac{NSB}{2}}\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot \tau^{.5}\cdot FOV_{deg}}{N_{across\ detector}^{.5}}}$$

which simplifies to

$$\frac{S_{Pixel}}{S_{Noise}} = \frac{0.7784\cdot 2.512^{\frac{NSB}{2}}\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot N_{across\ detector}^{.5}}{2.512^{OB}\cdot AV\cdot \tau^{.5}} > SNR$$

Solving for OB gives

$$2.512^{OB} = \frac{0.7784\cdot 2.512^{\frac{NSB}{2}}\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot N_{across\ detector}^{.5}}{\tau^{.5}\cdot AV\cdot SNR}$$

which results in a simple equation for the minimum detectable size using the assumed velocity filter with streak compression and multiple frames.

$$OB = -0.2720 + \frac{NSB}{2} + 2.5\cdot LOG(D_{Tel}) + 1.25\cdot LOG(e_t) + 1.25\cdot LOG(BW) + 1.25\cdot LOG(e_d)$$
$$+1.25\cdot \log(N_{across\ detector}) - 1.25\cdot \log(\tau) - 2.5\cdot LOG(AV) - 2.5\cdot LOG(SNR)$$

Including the atmospheric losses this becomes

$$OB = -0.2720 + \frac{NSB}{2} + 2.5 \cdot LOG(D_{Tel}) + 1.25 \cdot LOG(e_t) + 1.25 \cdot LOG(BW) + 1.25 \cdot LOG(c_d) + 1.25 \cdot \log(N_{across\ detector}) - 1.25 \cdot \log(\tau) - 2.5 \cdot LOG(AV) - 2.5 \cdot LOG(SNR) - eX$$

B3.5 Pseudo-Tracking TDI Mode

In the pseudo-tracking mode the signal is concentrated in a single pixel and is integrated the entire time the object is within the field of view. The time the object stays in the field of view is found by dividing the field of view of the telescope by the angular velocity of the object.

$$T = Time = \frac{FOV}{AV}$$

The available signal is then given by

$$S_{total} = \frac{7.853 \times 10^{6} \cdot 2.512^{-OB} \cdot D_{tel}^{2} \cdot e_t \cdot BW \cdot e_d \cdot FOV}{AV}$$

In the pseudo-tracking mode where the signal is integrated in a single pixel, the background signal is only due to the signal collected in that pixel and not a sum of many pixels. The background signal per second per pixel is

$$NSB_{per\ time} = \frac{NSB_{Time}}{N_{Pixels\ in\ detector}} = \frac{1.0178 \times 10^{14} \cdot 2.512^{-NSB} \cdot D_{tel}^{2} \cdot e_t \cdot BW \cdot e_d \cdot FOV_{deg}^{2}}{N_{Pixels\ in\ detector}}$$

The background signal of interest is then given by

$$NSB_{interest} = NSB_{per\ time} \cdot T = \frac{1.0178 \times 10^{14} \cdot 2.512^{-NSB} \cdot D_{tel}^{2} \cdot e_t \cdot BW \cdot e_d \cdot FOV_{deg}^{2}}{N_{Pixels\ in\ detector}} \frac{FOV}{AV}$$

which simplifies to

$$NSB_{interest} = NSB_{per\ time} \cdot T = \frac{1.0178 \times 10^{14} \cdot 2.512^{-NSB} \cdot D_{tel}^2 \cdot e_t \cdot BW \cdot e_d \cdot FOV_{deg}^3}{AV \cdot N_{Pixels\ in\ detector}}$$

The noise signal is then given by

$$S_{Noise} = \sqrt{NSB} = \frac{1.0089 \times 10^7 \cdot 2.512^{\frac{NSB}{2}} \cdot D_{tel} \cdot e_t^{.5} \cdot BW^{.5} \cdot e_d^{.5} \cdot FOV^{1.5}}{AV^{.5} \cdot N_{across\ detector}}$$

The signal to noise ratio is then found by

$$\frac{S_{total}}{S_{Noise}} = \frac{\dfrac{7.853 \times 10^6 \cdot 2.512^{-OB} \cdot D_{tel}^2 \cdot e_t \cdot BW \cdot e_d \cdot FOV}{AV}}{\dfrac{1.0089 \times 10^7 \cdot 2.512^{\frac{NSB}{2}} \cdot D_{tel} \cdot e_t^{.5} \cdot BW^{.5} \cdot e_d^{.5} \cdot FOV^{1.5}}{AV^{.5} \cdot N_{across\ detector}}}$$

which simplifies to

$$\frac{S_{Pixel}}{S_{Noise}} = \frac{0.7784 \cdot 2.512^{\frac{NSB}{2}} \cdot D_{tel} \cdot e_t^{.5} \cdot BW^{.5} \cdot e_d^{.5} \cdot N_{across\ detector}}{2.512^{OB} \cdot AV^{.5} \cdot FOV^{.5}} > SNR$$

Solving for OB gives

$$2.512^{OB} = \frac{0.7784 \cdot 2.512^{\frac{NSB}{2}} \cdot D_{tel} \cdot e_t^{.5} \cdot BW^{.5} \cdot e_d^{.5} \cdot N_{across\ detector}}{AV^{.5} \cdot FOV^{.5} \cdot SNR}$$

which results in a simple equation for the minimum detectable optical brightness for the pseudo-tracking mode of operation:

$$OB = -0.2720 + \frac{NSB}{2} + 2.5 \cdot LOG(D_{Tel}) + 1.25 \cdot LOG(e_t) + 1.25 \cdot LOG(BW) + 1.25 \cdot LOG(e_d) + 2.5 \cdot \log(N_{across\ detector}) - 1.25 \cdot LOG(AV) - 1.25 \cdot \log(FOV) - 2.5 \cdot LOG(SNR)$$

By including the atmospheric loss terms we get:

$$OB = -0.2720 + \frac{NSB}{2} + 2.5 \cdot LOG(D_{Tel}) + 1.25 \cdot LOG(e_t) + 1.25 \cdot LOG(BW) + 1.25 \cdot LOG(e_d) + 2.5 \cdot \log(N_{across\ detector}) - 1.25 \cdot LOG(AV) - 1.25 \cdot \log(FOV) - 2.5 \cdot LOG(SNR) - eX$$

B3.6 Tracking

In the tracking mode the signal is integrated as long as the telescope tracks at that given velocity. Therefore the signal is given by

$$S_{total} = 7.853 \times 10^6 \cdot 2.512^{-OB} \cdot D_{tel}^2 \cdot e_t \cdot BW \cdot e_d \cdot T_{tracking}$$

The background signal is also found by multiplying the signal per time by the amount of time tracking:

$$NSB_{per\ time} = \frac{NSB_{Time}}{N_{Pixels\ in\ detector}} = \frac{1.0178 \times 10^{14} \cdot 2.512^{-NSB} \cdot D_{tel}^2 \cdot e_t \cdot BW \cdot e_d \cdot FOV_{deg}^2}{N_{Pixels\ in\ detector}}$$

$$NSB_{interest} = NSB_{per\ time} \cdot T = \frac{1.0178 \times 10^{14} \cdot 2.512^{-NSB} \cdot D_{tel}^2 \cdot e_t \cdot BW \cdot e_d \cdot FOV_{deg}^2}{N_{Pixels\ in\ detector}} \cdot T_{tracking}$$

The background noise is given by

$$S_{Noise} = \sqrt{NSB} = \frac{1.0089\times10^{7}\cdot 2.512^{\frac{NSB}{2}}\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot FOV_{deg}\cdot T_{tracking}^{.5}}{N_{across\ detector}}$$

$$\frac{S_{total}}{S_{Noise}} = \frac{7.853\times10^{6}\cdot 2.512^{-OB}\cdot D_{tel}^{2}\cdot e_t\cdot BW\cdot e_d\cdot T_{tracking}}{\frac{1.0089\times10^{7}\cdot 2.512^{\frac{NSB}{2}}\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot FOV_{deg}\cdot T_{tracking}^{.5}}{N_{across\ detector}^{.5}}}$$

$$\frac{S_{Pixel}}{S_{Noise}} = \frac{0.7784\cdot 2.512^{\frac{NSB}{2}}\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot N_{across\ detector}\cdot T_{tracking}^{.5}}{2.512^{OB}\cdot FOV} > SNR$$

Solving for OB,

$$2.512^{OB} = \frac{0.7784\cdot 2.512^{\frac{NSB}{2}}\cdot D_{tel}\cdot e_t^{.5}\cdot BW^{.5}\cdot e_d^{.5}\cdot N_{across\ detector}\cdot T_{tracking}^{.5}}{FOV\cdot SNR}$$

This simplifies to an equation for the minimum optical brightness for the tracking mode

$$OB = -0.2720 + \frac{NSB}{2} + 2.5\cdot LOG(D_{Tel}) + 1.25\cdot LOG(e_t) + 1.25\cdot LOG(BW) + 1.25\cdot LOG(e_d) + 2.5\cdot \log(N_{across\ detector}) + 1.25\cdot \log(T_{tracking}) - 2.5\cdot \log(FOV) - 2.5\cdot LOG(SNR)$$

Including atmospheric losses we get

$$OB = -0.2720 + \frac{NSB}{2} + 2.5\cdot LOG(D_{Tel}) + 1.25\cdot LOG(e_t) + 1.25\cdot LOG(BW) + 1.25\cdot LOG(e_d) + 2.5\cdot \log(N_{across\ detector}) + 1.25\cdot \log(T_{tracking}) - 2.5\cdot \log(FOV) - 2.5\cdot LOG(SNR) - eX$$

These equations give the faintest optical magnitudes that can be detected against the night sky background for the different detection methods. Some of these equations do not give valid answers if the object does not cross several pixels per frame.

B4 MINIMUM DETECTABLE OPTICAL BRIGHTNESS AT VARIOUS SITES

The available information on the characteristics at various sites is shown in Table B3.

Table B3. Available Information on Participating Optical Sites

Site	NSB	eX	Diam	et	BW	ed	Field of View	Frame Rate
WPAFB	21	0.3	2.54	0.89	6200	0.072	0.2	0.033
ETS	22.23	0.25	0.79	0.89	6200	0.072	1	0.033
ETS	22.23	0.25	0.79	0.89	6200	0.072	0.5	0.033
AMOS	22.23	0.2	0.56	0.6	6200	0.142	0.5	0.033
Malabar	20.4	0.35	1.2	0.85	3500	0.142	0.5	0.033
Malabar WFOV	20.4	0.35	0.5	0.69	5400	0.083	3.5	0.033
SOR	19.7	0.25	1.5	0.85	6200	0.142	0.72	0.033
SOR 2	19.7	0.25	3.5	0.85	6200	0.142	0.31	0.033

Using the equations derived in the previous sections, the faintest detectable optical brightness for the different sites are given in the table below

Table B4. Visual Magnitudes of the faintest Detectable Object for Participating Sites and Various Methods at 500 km and Signal to Noise Ratio of 5

Site	Range (km)	SNR	Single Pixel	AVF Frames	AVF Pixels only	AVF Both	PS Track	Track 1 sec	Track 10 sec
WPAFB	500	5	14.82	15.87	17.23	18.29	20.71	21.5*	22.7*
ETS	500	5	13.84	15.77	15.39	17.32	18.86	18.78	20.03
ETS	500	5	13.84	15.40	15.76	17.32	19.24	19.54	20.79
AMOS	500	5	13.67	15.23	15.60	17.15	19.07	19.37	20.62
Malabar	500	5	13.32	14.87	15.24	16.79	18.71	19.01	20.26
Malabar WFOV	500	5	12.20	14.81	13.06	15.67	16.53	15.78	17.03
SOR	500	5	13.62	15.37	15.34	17.09	18.81	18.92	20.17
SOR 2	500	5	14.54	15.83	16.72	18.01	20.19	20.75	22.00

(*) not available at Wright Patterson.

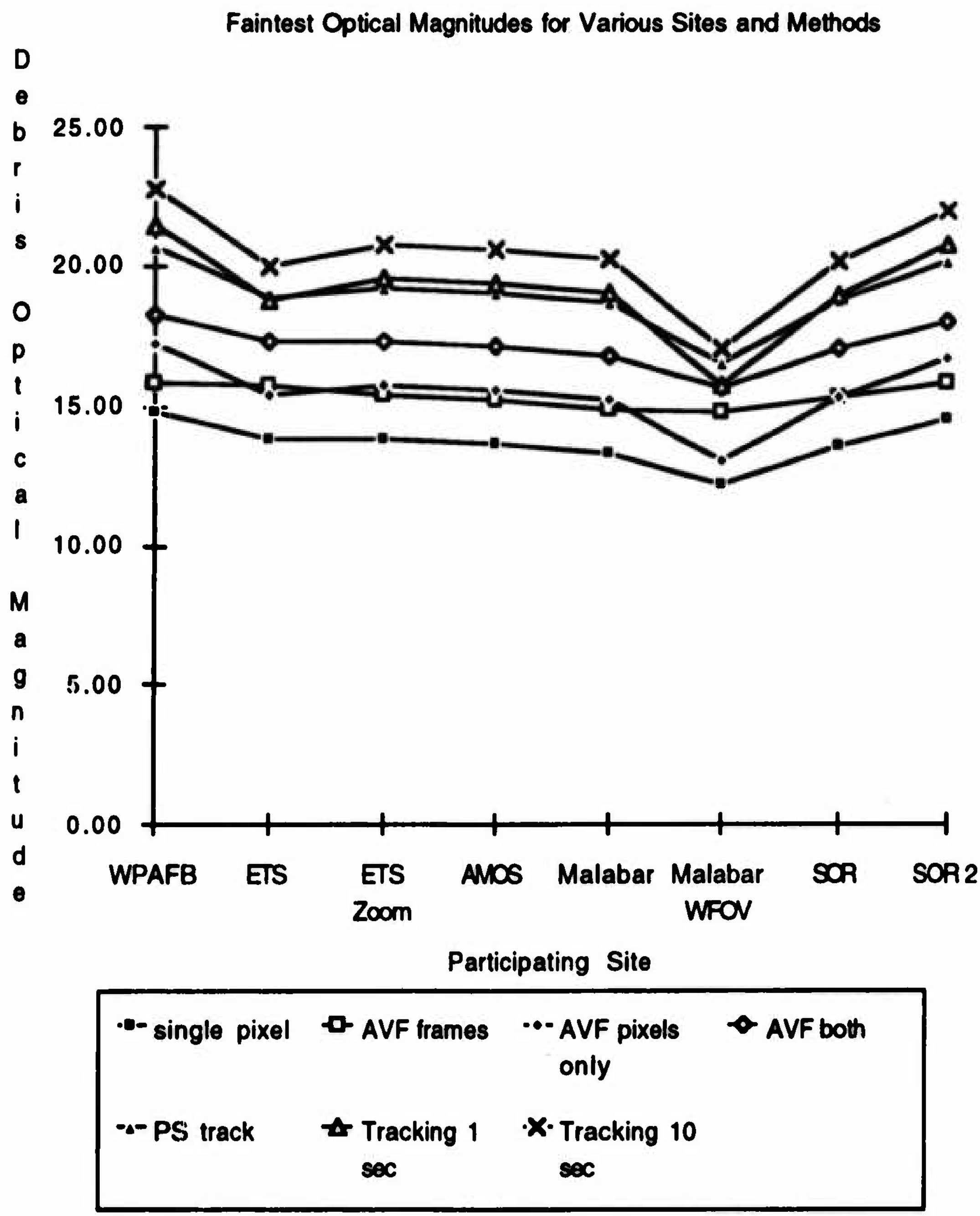

Figure B14. Faintest Detectable Object Brightness for Participating Sites and Various Methods at 500 km and with a Signal to Noise Ratio of 5

The results of the methods used to detect and enhance the data are dependent on the angular velocity of the debris. The minimum detectable object brightness for Wright Patterson at various altitudes and a signal to noise ratio of 5 is given below.

Table B5. Faintest Detectable Object Brightness for the Wright Patterson Debris Detection System at Various Altitudes and a Signal to Noise Ratio of 5.

Range (km)	Angular Velocity	SNR	Single Pixel	AVF Frames	AVF Pixels only	AVF Both	PS Track	Track 1 sec (*)	Track 10 sec (*)
200	2.225	5	13.43	13.97	16.35	16.90	19.83	21.13	22.38
300	1.471	5	13.87	14.64	16.58	17.35	20.05	21.13	22.38
400	1.094	5	14.20	15.13	16.74	17.67	20.21	21.13	22.38
500	0.868	5	14.45	15.50	16.86	17.92	20.34	21.13	22.38
600	0.718	5	14.65	15.81	16.97	18.13	20.44	21.13	22.38
700	0.610	5	14.83	16.08	17.06	18.30	20.53	21.13	22.38
800	0.530	5	14.98	16.31	17.13	18.46	20.61	21.13	22.38
900	0.467	5	15.12	16.51	17.20	18.59	20.67	21.13	22.38
1000	0.417	5	15.24	16.70	17.26	18.72	20.74	21.13	22.38
1500	0.268	5	15.72	17.42	17.50	19.20	20.98	21.13	22.38
2000	0.193	5	16.08	17.95	17.68	19.55	21.15	21.13	22.38
2500	0.149	5	16.36	18.37	17.82	19.83	21.29	21.13	22.38
3000	0.120	5	16.59	18.72	17.94	20.07	21.41	21.13	22.38
4000	0.085	5	16.97	19.29	18.13	20.45	21.60	21.13	22.38
5000	0.064	5	17.28	19.76	18.28	20.76	21.76	21.13	22.38
6000	0.050	5	17.55	20.15	18.41	21.02	21.89	21.13	22.38
7000	0.041	5	17.77	20.49	18.53	21.25	22.00	21.13	22.38
8000	0.034	5	17.98	20.80	18.63	21.45	22.10	21.13	22.38
10000	0.024	5	18.34	21.34	18.81	21.81	22.28	21.13	22.38

(*) not available at Wright Patterson.

The equations used are not accurate beyond an altitude of 16000 km for Wright Patterson because the debris does not necessarily change pixels between frames. Other sites will have different altitudes where this occurs. It is a function of the field of view, the number of pixels and the frame time.

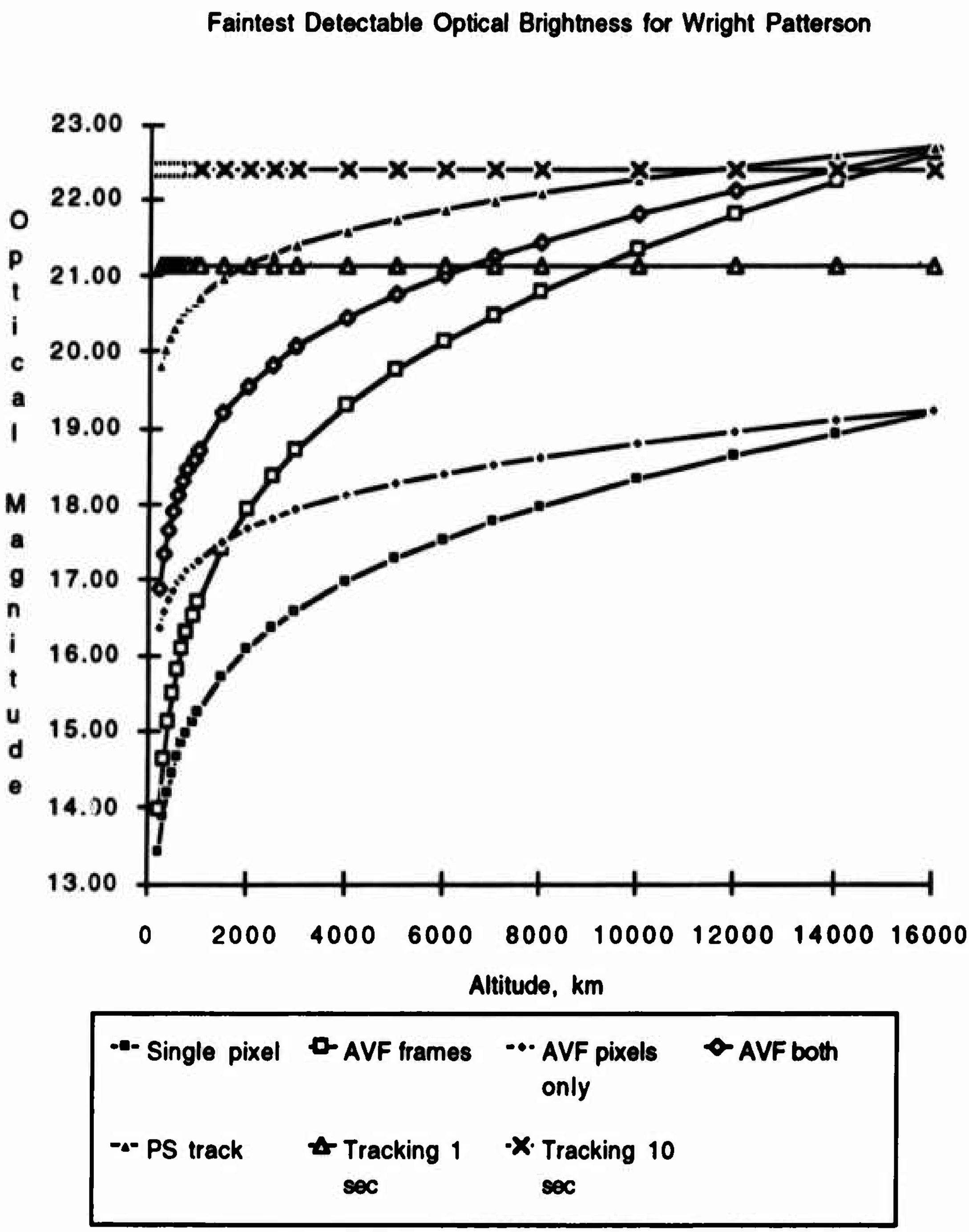

Figure B15. Faintest Detectable Object Brightness for the Wright Patterson Debris Detection System at Various Altitudes and a Signal to Noise Ratio of 5

B5 OPTICAL BRIGHTNESS OF DEBRIS TO SIZE

The magnitude of the brightness of a piece of space debris is given by

$$M_{deb} = -M_{sun} - 2.5 \log\left(\frac{Alb \cdot A_{obj} \cdot F(\theta)}{r^2}\right) + eX$$

where:

M_{deb} = Optical magnitude of debris (optical mag)
M_{sun} = Sun's apparent in-band magnitude (optical mag)
Alb = Albedo of the debris
A = Visible area of the object (m^2)
$F(\theta)$ = Phase function
r = Range to debris (m)
eX = Degradation due to atmospheric extinction.

At Wright Patterson the S-20 type photocathode used in the second generation image intensifiers is sensitive between 3000 Angstroms and 9200 Angstroms for a bandwidth of 6200 Angstroms. The optical magnitude of the solar radiation at the wavelengths that a S-20 image intensifier is sensitive is -26.77.

The second term of the equation involving the albedo, the area, and the phase function includes the reflected light from the debris. The range squared loss is due to the spreading of the reflected light. The average albedo of debris is found by Dr. Karl Henize's GEODSS Data to be 0.08. The phase function is assumed to be a Lambertian Scatterer. Analysis by Carl Henize of NASA indicates that the Lambertian approximation is within the expected error bars for debris measurements.[29] The phase function for a Lambertian Scatterer is

$$F(\theta) = \frac{2}{3\pi^2}\left[(\pi-\theta) \cos \theta + \sin \theta\right]$$

where θ is the angle between the sun and the telescope. For the geometry required for optical measurements (dusk or dawn terminator, near vertical staring) the sun is approximately 18 degrees below the horizon (astronomical twilight) and hence the phase angle is approximately 72 degrees, which gives us F(72) = 0.1036.

The last term defines the loss of light through the atmosphere, which is calculated by the optical depth of the atmosphere times the extinction coefficient. At zenith and depending on atmospheric conditions the extinction of the signal is decreased by 20 percent to 35 percent. For very hazy or muggy nights this can be decreased significantly more. For the Lincoln Laboratories ETS site this product is calculated from measurements to be 0.25. An estimate for Wright Patterson extinction is 0.30.

Inputing these values for Wright Patterson into the optical brightness equation we get

$$M_{deb} = -26.77 - 2.5 \log\left(\frac{0.08 \cdot A_{obj} \cdot 0.1036}{r^2}\right) + 0.30$$

where:

M_{deb} = Optical magnitude of debris
A = Area of the debris
r = Range in compatible units.

For r in kilometers and debris area in square centimeters this becomes

$$M_{deb} = -26.77 - 2.5 \log\left(\frac{0.08 \cdot A_{obj_{cm}} \cdot 0.1036}{r_{km}^2 \cdot 10^{10}}\right) + 0.30$$

For a 1 cm object at 500 km this equates to

$$M_{deb} = -26.77 - 2.5 \log\left(\frac{0.08 \cdot 0.79 \cdot 0.1036}{2.5 \text{ X } 10^{15}}\right) + 0.30$$

Which equals

$$M_{deb}\ 1\text{ cm} = 17.48$$

In order to calculate the debris size from the optical signature we must invert this equation. Rearranging to find the apparent size in terms of optical magnitude

$$M_{deb} + 26.77 - 0.30 = -2.5 \log\left(\frac{8.29 \text{ X } 10^{-13} \cdot A_{obj_{cm}}}{r_{km}^2}\right)$$

This reduces to

$$-0.2\, M_{deb} + 0.7992 = \log d\, cm - \log r\, km$$

which results in a simple equation defining optical brightness with apparent size:

$$D_{cm} = r_{km} \cdot 10^{\left(-0.2\, M_{deb} + 0.7992\right)}$$

Applying this to the faintest optical magnitude detected, the smallest detectable object can be determined. Listed below is the smallest detectable size of object for the various sites using the various methods.

Table B6. Minimum Detectable Size (in cm) for Participating Sites and Various Methods at 500 km and Signal to Noise Ratio of 5.

Site	Single Pixel	AVF Frames	AVF Pixels only	AVF both	PS Track	Track 1 sec	Track 10 sec
WPAFB	3.43	2.11	1.13	0.69	0.23	0.16	0.09
ETS	5.36	2.21	2.63	1.08	0.53	0.55	0.31
ETS Zoom	5.36	2.62	2.21	1.08	0.45	0.39	0.22
AMOS	5.79	2.83	2.39	1.17	0.48	0.42	0.24
Malabar	6.83	3.34	2.82	1.38	0.57	0.50	0.28
Malabar WFOV	11.45	3.44	7.69	2.31	1.55	2.20	1.24
SOR	5.95	2.66	2.69	1.20	0.54	0.52	0.29
SOR 2	3.89	2.15	1.43	0.79	0.29	0.22	0.13

Table B7. Minimum Detectable Size (in cm) for Wright patterson at Various Altitudes and Various Methods (Noise Ratio of 5).

Altitude	single pixel	AVF frames	AVF pixels only	AVF both	PS track	Tracking 1 sec	Tracking 10 sec
200	2.60	2.02	0.67	0.53	0.14	0.07	0.04
300	3.17	2.23	0.91	0.64	0.18	0.11	0.06
400	3.65	2.38	1.13	0.74	0.23	0.15	0.08
500	4.06	2.50	1.33	0.82	0.27	0.19	0.10
600	4.43	2.60	1.53	0.90	0.31	0.22	0.13
700	4.77	2.68	1.71	0.96	0.35	0.26	0.15
800	5.07	2.76	1.89	1.03	0.38	0.30	0.17
900	5.36	2.82	2.06	1.08	0.42	0.34	0.19
1000	5.63	2.88	2.22	1.14	0.45	0.37	0.21
1500	6.76	3.10	2.98	1.37	0.60	0.56	0.31
2000	7.67	3.24	3.66	1.55	0.74	0.75	0.42
2500	8.42	3.34	4.29	1.70	0.87	0.93	0.52
3000	9.07	3.41	4.88	1.83	0.99	1.12	0.63
4000	10.14	3.49	5.96	2.05	1.20	1.49	0.84
5000	11.00	3.52	6.94	2.22	1.40	1.87	1.05
6000	11.70	3.53	7.84	2.36	1.58	2.24	1.26
7000	12.28	3.51	8.68	2.48	1.75	2.61	1.47
8000	12.77	3.48	9.46	2.58	1.91	2.99	1.68
10000	13.53	3.40	10.89	2.73	2.20	3.73	2.10
12000	14.06	3.29	12.16	2.84	2.46	4.48	2.52
14000	14.40	3.15	13.29	2.91	2.69	5.23	2.94
16000	14.59	3.01	14.30	2.95	2.89	5.97	3.36

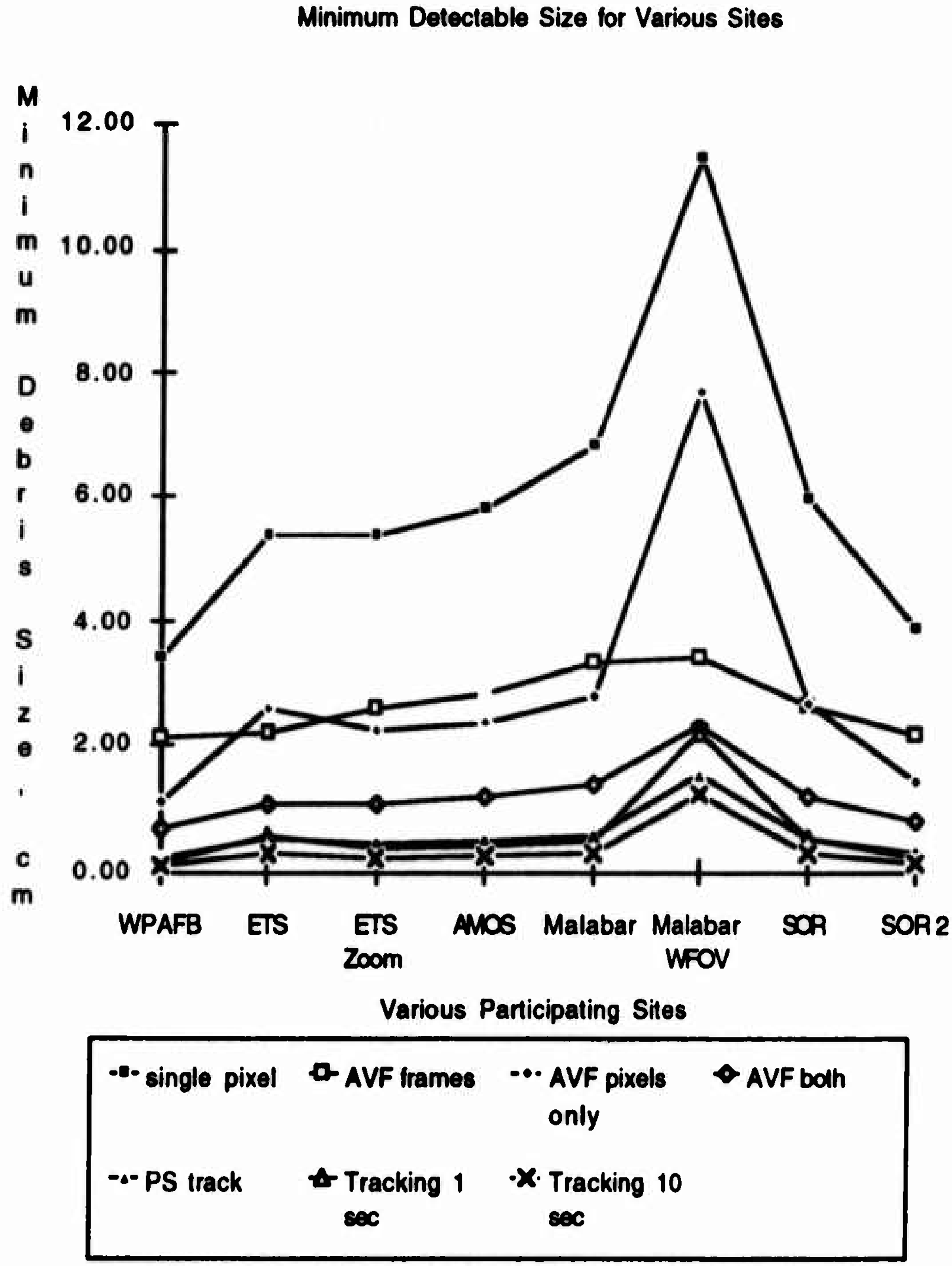

Figure B16. Minimum Detectable Size for Participating Sites and Various Methods at 500 km and Signal to Noise Ratio of 5

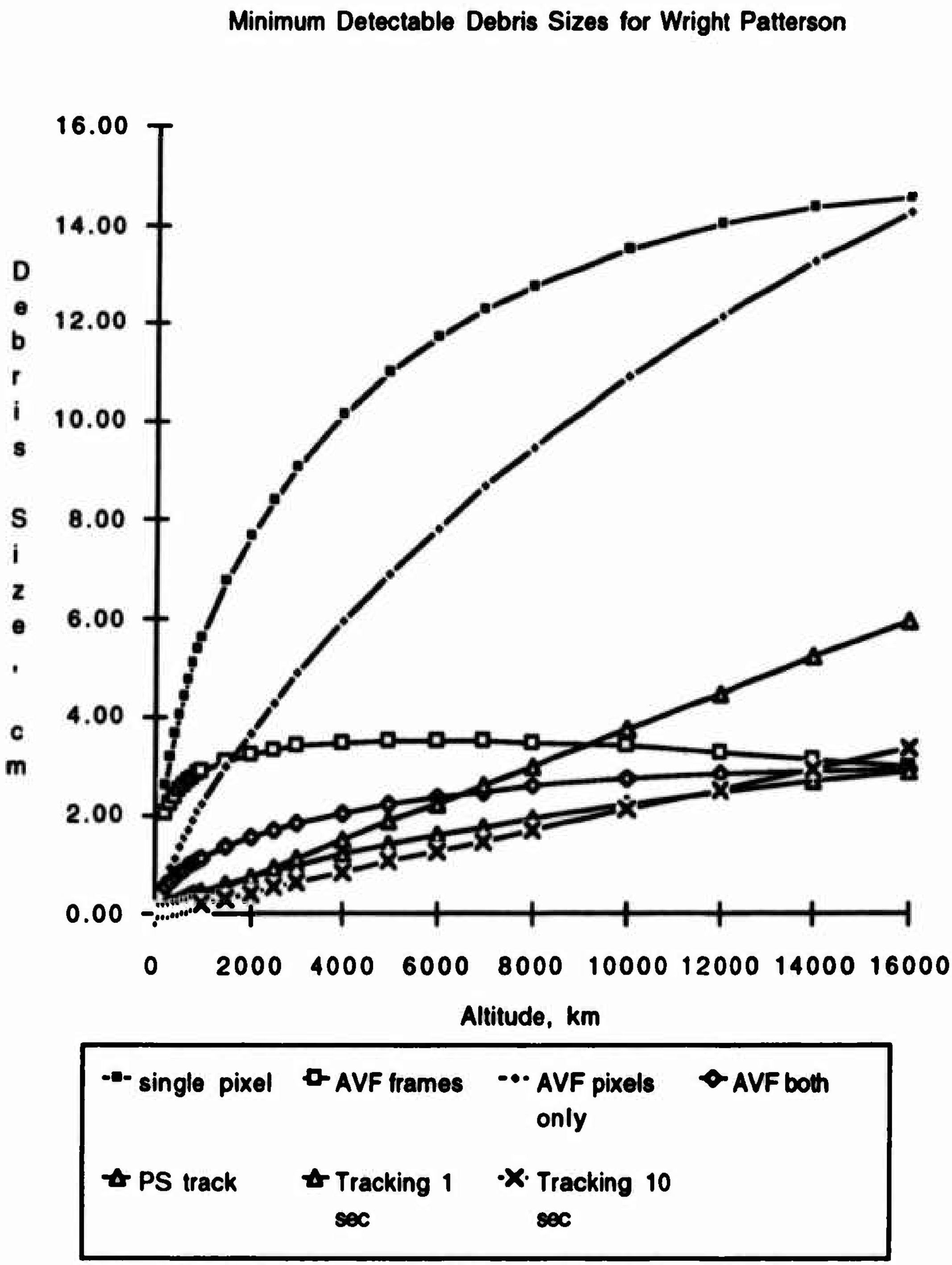

Figure B17. Minimum Detectable Size for Wright Patterson at Various Altitudes and Various Methods (Signal to Noise Ratio of 5)

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